16 MAUG

16.1 Introduction

Maug consists of 3 separate islands, which are actually the rim of a submerged caldera of a large volcano (Fig. 16.1a). Known as East (Higashi-shima), West (Nishi-shima), and North (Kita-shima) Islands, they are located at 20°02′ N, 145°13′ E and 67 km southeast of Farallon de Pajaros and 41 km northwest of Asuncion. The outer diameter of this circle of islands is ~ 3.3 km, and the inner diameter of the submerged caldera is ~ 2.2 km. With a combined land area of 2.14 km^2, these islands are the smallest islands of the Commonwealth of the Northern Mariana Islands (CNMI). The highest elevation is 227 m on the ridge of the crater rim on North Island. The highest elevations of East and West Islands are 215 m and 178 m. These 3 islands are each characterized by a narrow central ridge with slopes on either side ending in steep cliffs along their coasts (Fig. 16.1b).

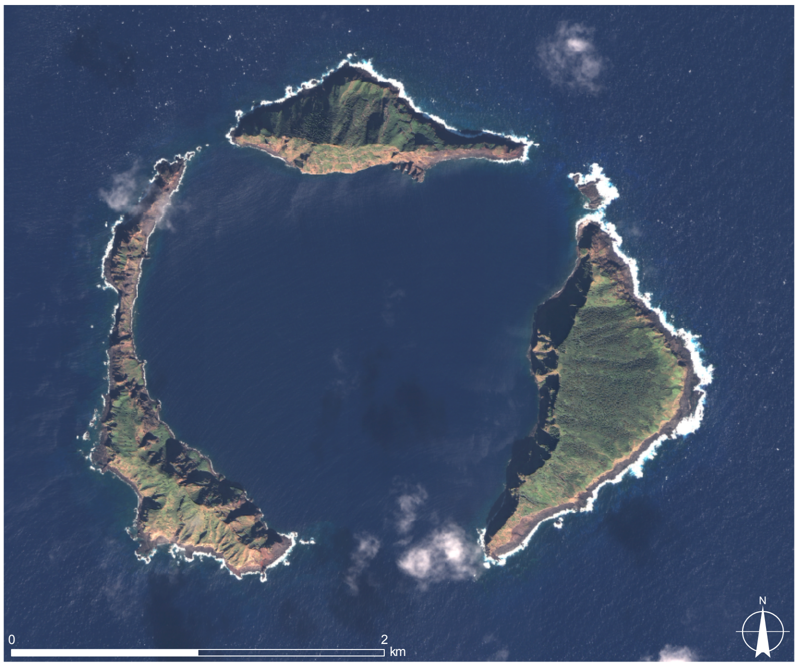


Figure 16.1a. Satellite image of Maug (© 2003 DigitalGlobe Inc. All rights reserved).

Figure 16.1b. A view of Maug from the south, as seen from the NOAA Ship *Hi`ialakai* in 2007. *NOAA photo*

16.1.1 History and Demographics

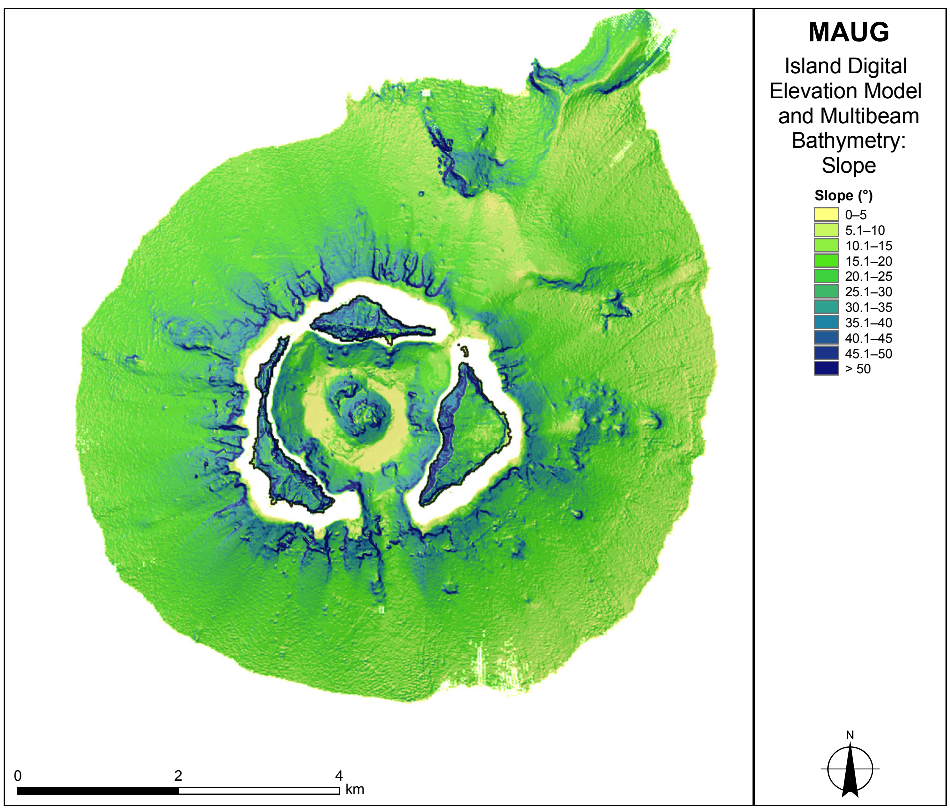
There has been no permanent inhabitation of Maug since 1695, when Spain forced all inhabitants of the northern islands of the Mariana Archipelago to relocate to Guam (Rogers 1995). In 1909, while under German administration, Maug was leased to the Pagan Gesellschaft for exploitation of bird plumage for a period of 3 years, along with Agrihan, Asuncion, Guguan, Farallon de Pajaros, Farallon de Medinilla, and Sarigan. During this time, Japanese bird catchers employed on these islands may have been resident there temporarily, and other fishing or hunting parties may have also periodically resided on Maug. Prior to and during World War II (1939–1945), a Japanese weather station and fish processing plant were established on Maug. Since 1978, inhabitation of Maug has been prohibited by the CNMI Constitution under Article XIV.

Maug falls within the Northern Islands Municipality of the CNMI, and the political history of Maug follows that of the CNMI as a whole, which is described in more detail in Chapter 1: "Introduction" and Chapter 8: "Saipan," Section 8.1.1: "History and Demographics."

16.1.2 Geography

Located at the northern end of the Mariana Archipelago, the 3 islands of Maug are formed by the exposed sections of the rim of a caldera that is largely submerged and 2.5 km wide. Each island is characterized by a central ridge, forming the rim of a caldera, with steep slopes on the inner flanks and more gentle slopes on the outer flanks (Fig. 16.1.2a).

Figure 16.1.2a. Combined slope map using the digital elevation model (grid cell size: 10 m) and multibeam bathymetry (grid cell size: 10 m) for Maug.



Maug forms a twin volcanic massif with Supply Reef, which lies 18 km to the northwest of Maug (Siebert and Simkin 2002–; see Figure 18.2.3a in Chapter 18: "Reefs and Banks of the CNMI"). Lava flows and pyroclastic deposits cut by radial dikes are exposed on the inner walls of the Maug caldera (Fig. 16.1.2b), while the outer flanks of this caldera are overlain with bedded ash deposits (Siebert and Simkin 2002–). North and West Islands are dominated by basaltic columns (Scripps 2009).

The island slopes of Maug are vegetated, covered mainly with coarse grass and patches of low-lying shrubs (Fig. 16.1.2c). The largest island, East Island, has coconut groves on its west coast and trees covering its high slopes. Areas of forest are also present along the shoreline of Maug and continue up ravines, while the steepest slopes of these islands are rocky with less vegetation (Mueller-Dombois and Fosberg 1998).

No volcanic eruptions have been recorded at Maug since the Spanish ship *Trinidad*, captained by Gómez de Espinosa, landed in 1522. However, exploration of the Mariana Archipelago in 2003 revealed active hydrothermal discharge within the Maug caldera (Embley et al. 2004).

West of East Island, a hydrothermal vent system appears to affect the temperature and quality of the water surrounding it. During MARAMP 2007, water samples were taken at a single location near this vent system to gain insight into the marine geochemistry of hydrothermal vents in the CNMI and the possible influences this specific vent system had on the surrounding benthic ecosystem (see Section 16.4: "Oceanography and Water Quality").

Figure 16.1.2b. A radial dike, the vertical column in the center of this photo, on Maug bisecting layers of lava flows (dark horizontal bands) and ash-rich lava units (rust-colored bands). *Photo courtesy of the NOAA Vents Program*

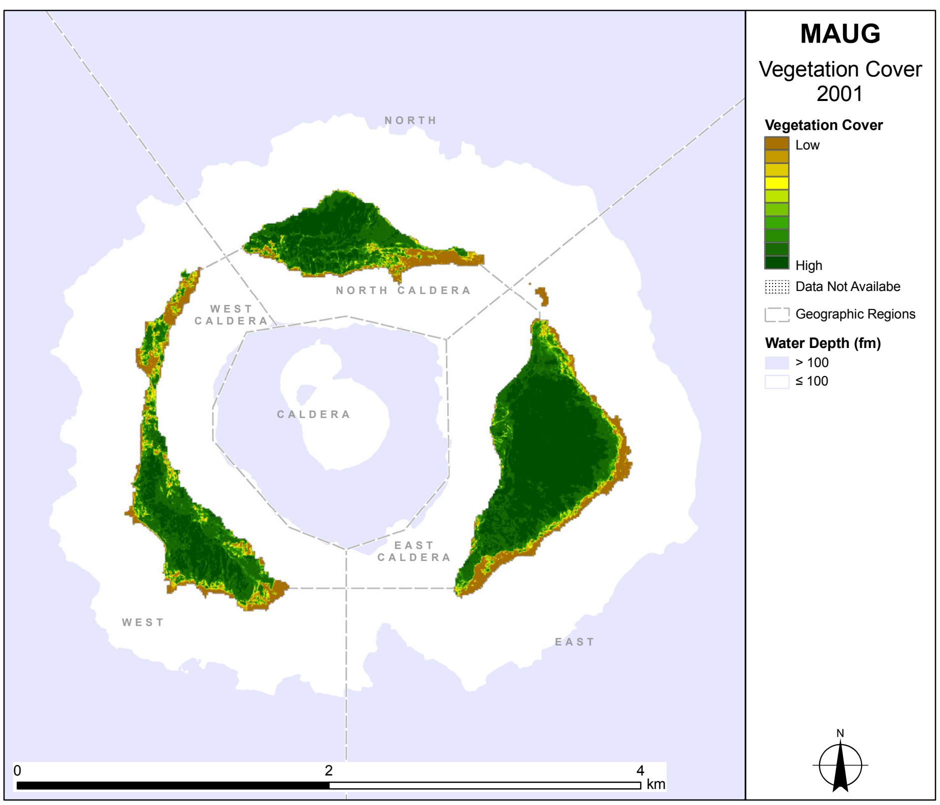


Figure 16.1.2c. Vegetation cover on Maug, derived using the Normalized Difference Vegetation Index from a satellite image (grid cell size: 4 m; IKONOS Carterra Geo Data 2001).

16.1.3 Environmental Issues on Maug

Maug is part of a protected reserve area established under Article XIV of the CNMI Constitution and managed by the CNMI Division of Fish and Wildlife. This legislation states that the islands of Maug are to be retained as uninhabited places, and no permanent structures can be built on these islands, except for the preservation and protection of natural resources (CNMI Constitution). Maug is preserved as a habitat for birds, wildlife, and plants. On these islands, 25 species of birds are protected, including two birds that breed on Maug, the Micronesian megapode (*Megapodius laperouse*), which is listed Federally as endangered (U.S. Fish and Wildlife Service) and locally as threatened or endangered (Berger et al. 2005), and the near-threatened (BirdLife International 2008) white-throated ground-dove (*Gallicolumba xanthonura*). Terrestrial plants present include several species endemic to the Mariana Archipelago, but none are endemic specifically to Maug (Pacific Protected Areas Database).

Because of Maug's isolation and lack of inhabitants, local anthropogenic impacts around these islands are thought to be few. However, non-native species, including several species of plants, rats, and goats are thought to have been introduced to these islands (Pacific Protected Areas Database). Fishing activity within the CNMI tends to be focused around the southern islands of the Mariana Archipelago, with multi-day fishing trips focusing on the islands and banks south of Guguan (Western Pacific Fishery Management Council 2009). While fishing at Maug is considered uncommon, fishing and diving have been observed at Maug during MARAMP cruises.

Maug became part of the Marianas Trench Marine National Monument, which was established in January 2009 by presidential proclamation. This Marine National Monument includes a Trench Unit, an Islands Unit, and a Vents Unit. The Islands Unit includes the waters and submerged lands of the islands of Maug, Asuncion, and Farallon de Pajaros.

16.2 Survey Effort

Extensive biological, physical, and chemical observations collected under the Mariana Archipelago Reef Assessment and Monitoring Program (MARAMP) have documented the conditions and processes influencing coral reef ecosystems around the islands of Maug since 2003. The spatial reach and time frame of these survey efforts are discussed in this section. The disparate areas around this island often are exposed to different environmental conditions. To aid discussions of spatial patterns of ecological and oceanographic observations that appear throughout this chapter, 7 geographic regions around

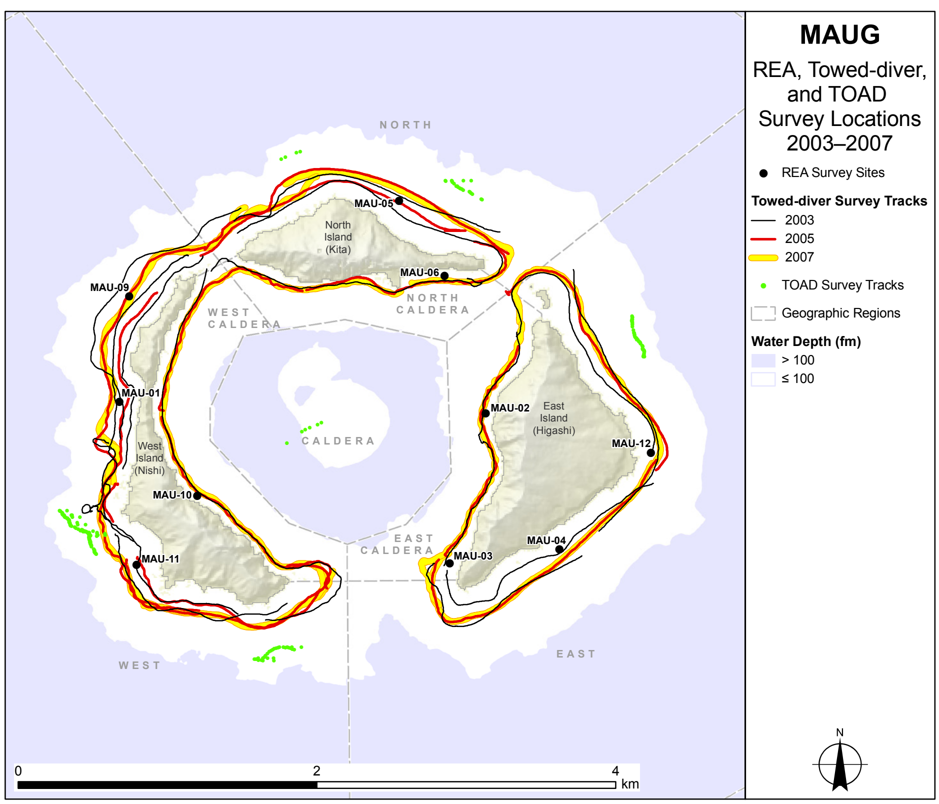


Figure 16.2a. Locations of the REA, towed-diver, and TOAD benthic surveys conducted around Maug during MARAMP 2003, 2005, and 2007. To aid discussion of spatial patterns, this map delineates 7 geographic regions: north, east, west, caldera, north caldera, east caldera, and west caldera.

Maug are delineated in Figure 16.2a; wave exposure and breaks in survey locations were considered when defining these geographic regions. This figure also displays the locations of the Rapid Ecological Assessment (REA) surveys, towed-diver surveys, and towed optical assessment device (TOAD) surveys conducted around Maug. Potential reef habitat around this island is represented by a 100-fm contour shown in white on this map.

Benthic habitat mapping data were collected around Maug using a combination of acoustic and optical survey methods. MARAMP benthic habitat mapping surveys conducted around Maug, Asuncion, Farallon de Pajaros, and Supply Reef with multibeam sonar covered a combined total area of 3856 km^2 in 2007. Optical validation and habitat characterization were completed using towed-diver and TOAD surveys that documented live coral cover, sand cover, and habitat complexity. The results of these efforts are discussed in Section 16.3: "Benthic Habitat Mapping and Characterization."

Information on the condition, abundance, diversity, and distribution of biological communities around Maug was collected using REA, towed-diver, and TOAD surveys. The results of these surveys are reported in Sections 16.5–16.8: "Corals and Coral Disease," "Algae and Algal Disease," "Benthic Macroinvertebrates," and "Reef Fishes." The numbers of surveys conducted during MARAMP 2003, 2005, and 2007 are presented in Table 16.2a, along with their mean depths and total survey areas or length. For one of the 11 towed-diver surveys conducted in 2007, GPS and depth data were not available, and, thus, depth and biological data collected during that survey cannot be shown on maps in this report.

Spatial and temporal observations of key oceanographic and water-quality parameters influencing reef conditions around Maug were collected using (1) two types of moored instruments designed for long-term observations of high-frequency variability of temperature, (2) closely spaced conductivity, temperature, and depth (CTD) profiles of the vertical structure of water properties, and (3) discrete water samples for nutrient and chlorophyll-*a* analyses. CTD casts were conducted during MARAMP 2003, 2005, and 2007, and water sampling was performed during MARAMP 2005 and 2007. Results for some casts and water samples are not presented in this report because either the data were redundant or erroneous or no data were produced (see Chapter 2: "Methods and Operational Background," Section 2.3: "Oceanography and Water Quality"). A summary of deployed instruments and collection activities is provided in Table 16.2b, and results are discussed in Section: 16.4: "Oceanography and Water Quality."

Table 16.2a. Numbers, mean depths (m), total areas (ha), and total length (km) of REA, towed-diver, and TOAD surveys conducted around Maug during MARAMP 2003, 2005, and 2007. REA survey information is provided for both fish and benthic surveys, the latter of which includes surveys of corals, algae, and macroinvertebrates.

Survey Type	Survey Detail	Year		
REA		**2003**	**2005**	**2007**
Fish	Number of Surveys	8	8	9
	Mean Depth (m)	13.1 (SD 1.5)	15.1 (SD 5.1)	13.4 (SD 1.6)
Benthic	Number of Surveys	9	8	9
	Mean Depth (m)	14.7 (SD 5.2)	15.1 (SD 5.1)	13.4 (SD 1.6)
Towed Diver		**2003**	**2005**	**2007**
	Number of Surveys	16	13	11
	Total Survey Area (ha)	29.0	24.2	25.1
	Mean Depth (m)	12.3 (SD 3.5)	13.9 (SD 2.9)	14.9 (SD 1.7)
TOAD		**2003**		
	Number of Surveys	6		
	Total Length (km)	1.85		

Table 16.2b. Numbers of oceanographic instruments deployed, shallow-water and deepwater CTD casts performed, and water samples collected around Maug during MARAMP 2003, 2005, and 2007. Two types of instruments were moored around Maug: sea-surface temperature (SST) buoy and subsurface temperature recorder (STR). Shallow-water CTD casts and water samples were conducted from the surface to a 30-m depth, and deepwater casts were conducted to a 500-m depth. Additional deepwater CTD cast information is presented in Chapter 3: "Archipelagic Comparisons."

Observation Type	Year						
Instruments	2003	2005		2007		2009	Lost
	Deployed	Retrieved	Deployed	Retrieved	Deployed	Retrieved	
SST	1	1	1	1	1	–	1
STR	1	1	4	4	5	5	–
CTD Casts	**2003**	**2005**		**2007**			**Total**
Shallow-water Casts	33	34		20			87
Deepwater Casts	–	10		4			14
Water Samples		**2005**		**2007**			**Total**
		14		9			23

Towed-diver Surveys: Depths

Figures 16.2b–e illustrate the locations and depths of towed-diver-survey tracks around Maug and should be referenced when further examining results of towed-diver surveys from MARAMP 2003, 2005, and 2007.

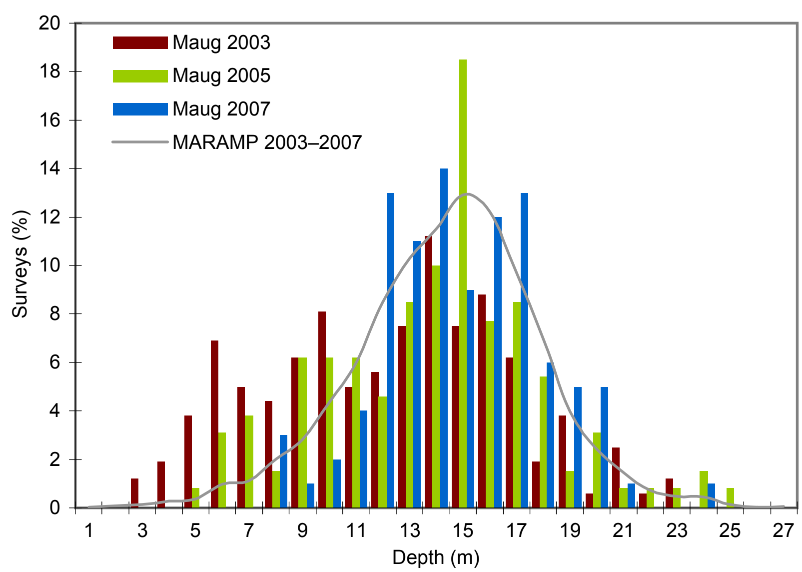


Figure 16.2b. Depth histogram plotted from mean depths of 5-min segments of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Mean segment depths were derived from 5-s depth recordings. Segments for which no depth was recorded were excluded. The grey line represents average depth distribution for all towed-diver surveys conducted around the Mariana Archipelago during MARAMP 2003, 2005, and 2007.

During MARAMP 2003, 16 towed-diver surveys were conducted along the forereef slopes around Maug (Figs. 16.2b and c). The mean depth of all survey segments was 12.3 m (SD 3.5), and the mean depths of individual surveys ranged from 5 m (SD 1.6) to 17 m (SD 6.7).

During MARAMP 2005, 13 towed-diver surveys were conducted along the forereef slopes around most of Maug (Figs. 16.2b and d). Mean depth of all survey segments was 13.9 m (SD 2.9), and the mean depths of individual surveys ranged from 7.6 m (SD 2.4) to 17.3 m (SD 4.5).

During MARAMP 2007, 11 towed-diver surveys were conducted along the forereef slopes of Maug (Figs. 16.2b and e). Mean depth of all survey segments was 14.9 m (SD 1.7), and the mean depths of individual surveys ranged from 12.4 m (SD 3) to 17.6 m (SD 4.6).

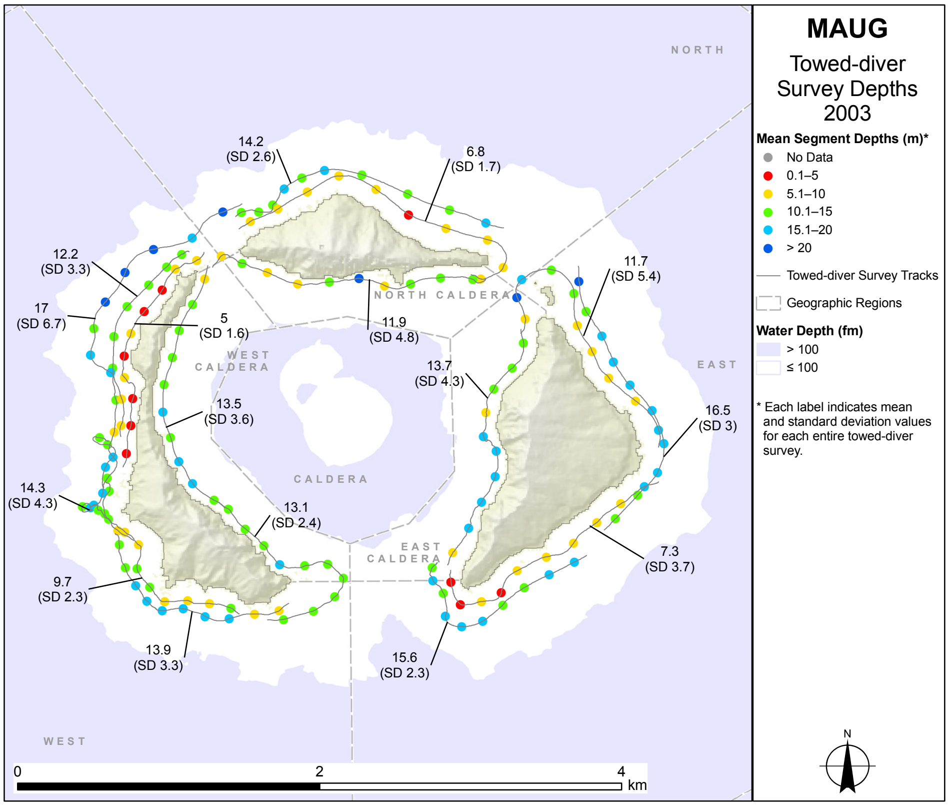


Figure 16.2c. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

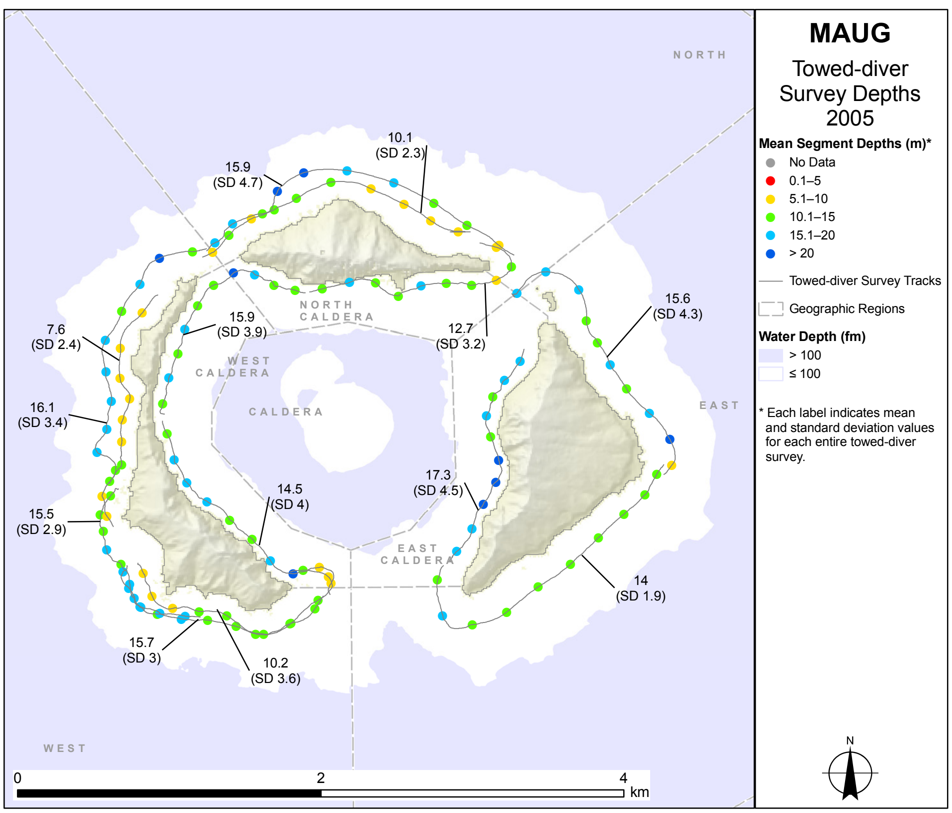
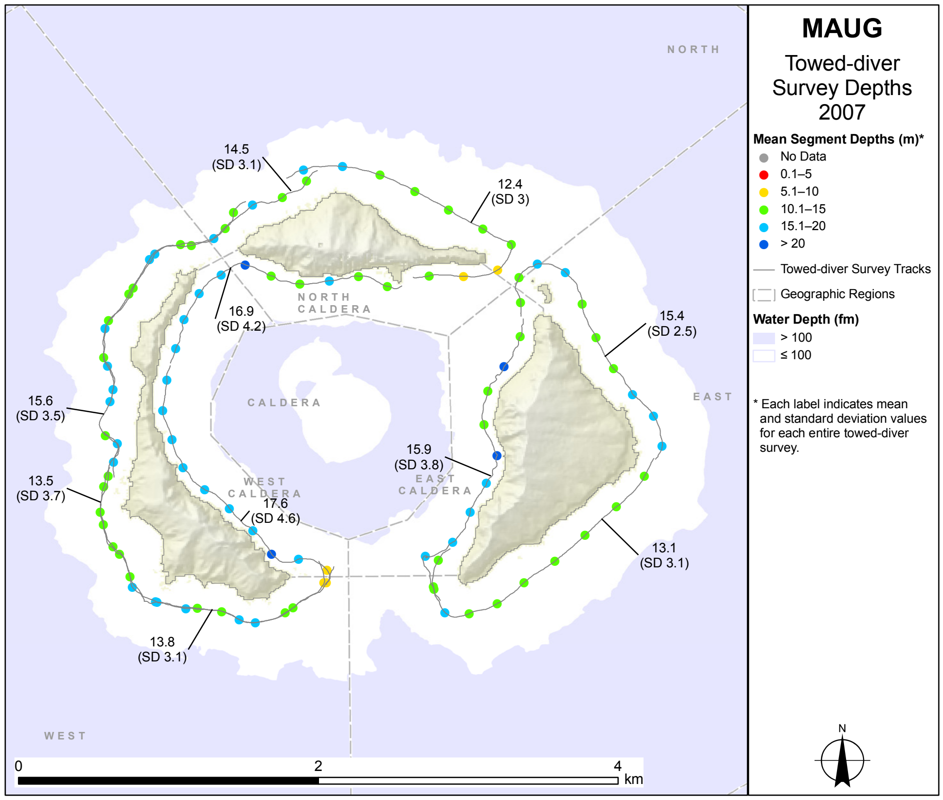


Figure 16.2d. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2005. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.

Figure 16.2e. Depths and tracks of towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2007. Towed-diver-survey tracks are color coded by mean depth for each 5-min segment. A black-text label shows the mean depth (and standard deviation) for each entire towed-diver survey. Each depth represents the depth of the benthic towboard during each survey; towboards are maintained nominally 1 m above the benthic substrate.



16.3 Benthic Habitat Mapping and Characterization

Benthic habitat mapping and characterization surveys around the islands of Maug were conducted during MARAMP 2003, 2005, and 2007 using acoustic multibeam sonar, underwater video and still imagery, and towed-diver observations. Acoustic multibeam sonar mapping provided bathymetric and backscatter data products over the depth range of ~ 10–2300 m. Multibeam coverage was almost complete around the 3 islands of Maug, including the seafloor within the submerged caldera. Optical validation and benthic characterization, via diver observations and both video and still underwater imagery, were performed using towed-diver surveys and TOAD deployments conducted at depths of ~ 1–150 m.

16.3.1 Acoustic Mapping

Multibeam acoustic bathymetry and backscatter imagery (Fig. 16.3.1a) collected by the Coral Reef Ecosystem Division (CRED) around Maug, Farallon de Pajaros, Asuncion and Supply Reef during MARAMP 2007 encompassed an area of 3856 km^2.

The 3 islands of Maug are formed by the caldera walls of a volcano, separated by narrow channels where the walls have collapsed. The multibeam bathymetry acquired around Maug reveals the submerged caldera at a depth of 200–240 m, from which a twin-peaked submarine dome rises to a depth of 20 m (Fig 16.3.1a, top panel). This submarine dome is likely the youngest feature of the volcano. The bathymetry data show the volcano's steep outer flanks, which descend rapidly to the depth of 1000 m within ~ 3 km of the shoreline. North and east of Maug, the seabed continues to descend until reaching a plateau at a depth of ~ 2100 m. Northwest of Maug at a depth of ~ 1700 m, the seabed descends to a channel, which separates Maug from a submarine volcanic cone 18 km northwest called Supply Reef (for more about this reef, see Chapter 18: "Reefs and Banks in the CNMI"). The bathymetry shows shallow ridges and channels on the flanks, and a steep-sided ridge is present northeast of North Island (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). North and west of Maug, the multibeam bathymetry reveals large blocks of material on the deep flanks. At 4–8 km southeast of East Island, the bathymetry data reveal an anomalous feature that rises from the main flanks at a depth of ~ 1600 m to a depth of 850 m. The 2 mechanisms that might have caused this feature are mass wasting (the movement of soil and surface materials by gravity) and volcanic activity.

Intensity of low-resolution backscatter around Maug was uniform throughout much of the area covered. Higher intensity backscatter values were observed around the edge of the small bank southeast of East Island and on the ridge northeast of North Island (Fig. 16.3.1a, bottom panel). Blocky materials on the flanks north and west of Maug had high-intensity backscatter, suggesting that these areas are characterized by hard substrates at or near the seabed surface.

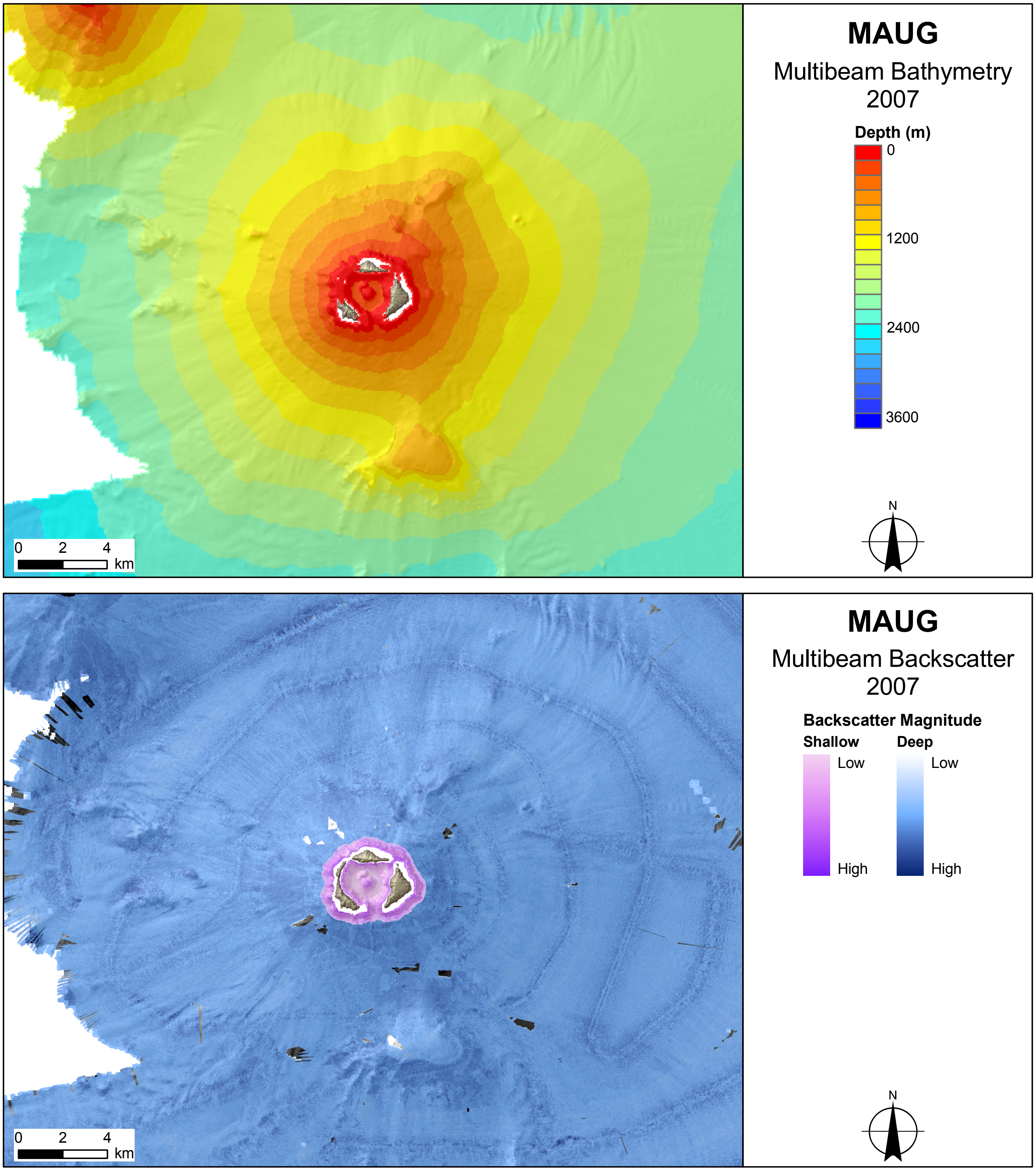
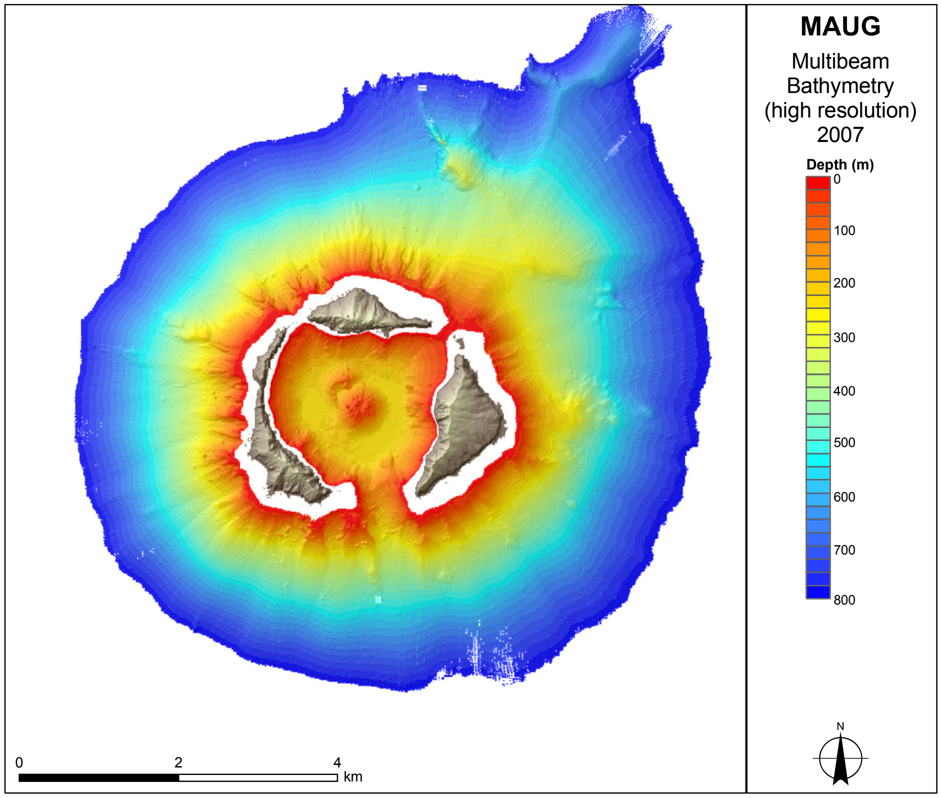


Figure 16.3.1a Gridded (*top*) multibeam bathymetry (grid cell size: 60 m) and (*bottom*) backscatter (grid cell size: 5 m) collected around Maug during MARAMP 2003 and 2007 at depths of ~ 10–2300 m. Shallow-backscatter data (shown in purple) were collected using a 240-kHz Reson SeaBat 8101 ER sonar, and deep backscatter data (shown in blue) were collected using a 30-kHz Kongsberg EM 300 sonar. For both sonars, light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates, such as unconsolidated sediment. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom or coral substrates.

High-resolution Multibeam Bathymetry and Derivatives

High-resolution multibeam data collected in the nearshore (depths of 0–800 m) waters around Maug (Fig. 16.3.1b) were combined into a grid at 10-m resolution to allow for the identification of fine-scale features. These data were used to derive benthic maps showing slope (Fig. 16.3.1c), rugosity (Fig. 16.3.1d) and bathymetric position index (BPI) zones (Fig. 16.3.1e). Together, these maps provide layers of information to characterize the benthic habitats around Maug.

Figure 16.3.1b. High-resolution multibeam bathymetry (grid cell size: 10 m) collected around Maug during MARAMP 2007. This 10-m bathymetry grid, clipped at 800 m, is used as the basis for slope, rugosity, and BPI derivatives.



The high-resolution bathymetry reveals additional detail on the flanks of Maug, including numerous ridges and ravines that incise the flanks and radiate out from the crater edge. These ridges have very steep slopes on either side (frequently > 50°) but are generally fairly short, extending for only up to 500 m away from the shore (Fig. 16.3.1c). High levels of rugosity are associated with these steep slopes (Fig. 16.3.1d). Below the ridges, the flanks are more uniform, with slopes of 10°–20° and low rugosity levels. Blocky material is shown along the upper flanks, particularly south of East and West Islands on either side of the southern channel that separates these islands. This material may have resulted from the failure of the caldera rim that created this channel. A smaller amount of material was shown within the caldera itself. The high-resolution data suggest that the southern channel is much deeper (~ 150 m) and wider than the 2 channels on either side of North Island (Fig. 16.3.1b).

On the flanks east of Maug, slope and rugosity maps show a complex area with steep slopes and high rugosity on the downslope side, likely a result of slumping from the crater wall. Similar but smaller features are shown southeast and west of Maug.

High-resolution bathymetry, slope, and rugosity reveal intricate topography of the twin-peaked dome that emerges from the submerged caldera.

BPI analysis highlights the dominance of slope zones around Maug, with crests and depressions created by the central dome and shallow ridges creating additional topographic complexity. A very small flat zone is identified on the caldera floor surrounding the central dome (Fig. 16.3.1e).

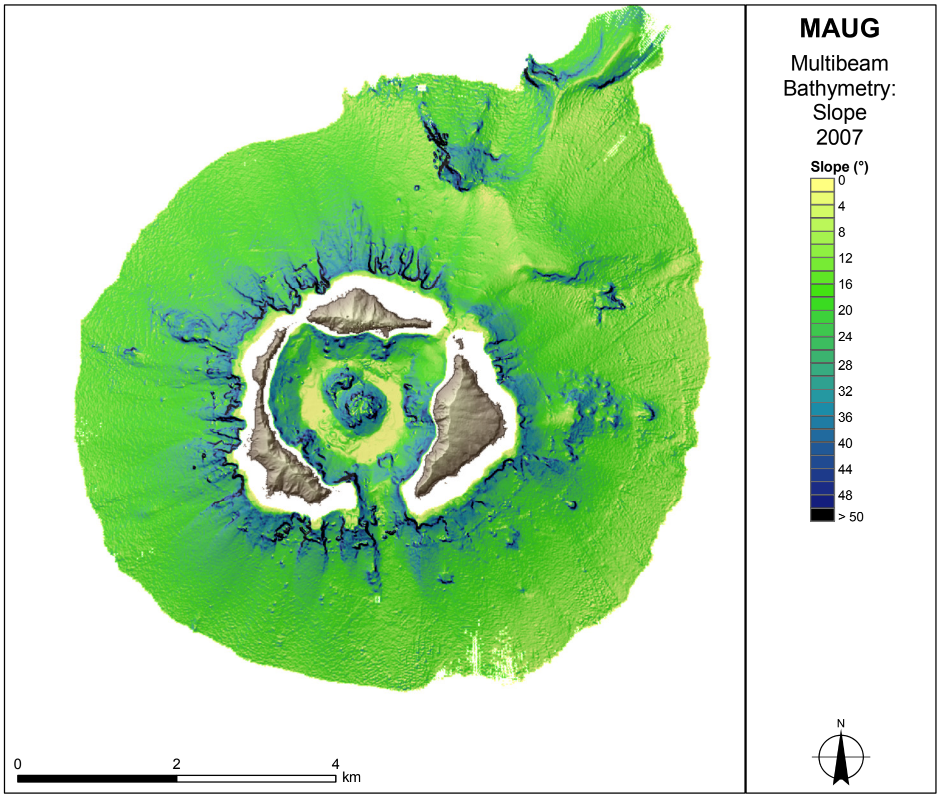


Figure 16.3.1c. Slope (°) of 10-m bathymetric grid around Maug. Derived from data collected in 2007, this map reflects the maximum rate of change in elevation between neighboring cells with the steepest slopes shown in the darkest blue shades and the flattest areas in yellow shades.

In the shallowest waters surveyed, the BPI analysis identifies reef crests (Fig, 16.3.1e). However, this classification is likely an artifact of the methodology, since no data are available for immediately inshore areas and no comparison can be made to the innermost cells of the grid. Instead, these areas probably should be characterized as slopes.

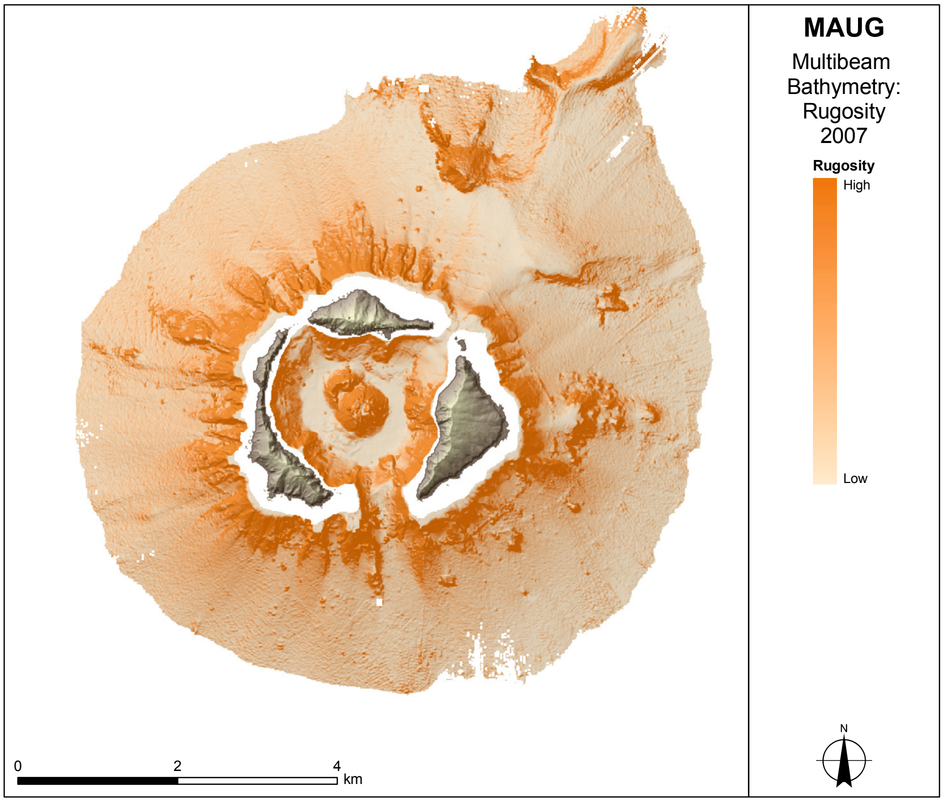


Figure 16.3.1d. Rugosity of 10-m bathymetric grid around Maug. Derived from data collected in 2007, these rugosity values are a measure of the ratio of surface area to planimetric area within a given cell's neighborhood and indicate topographic roughness.

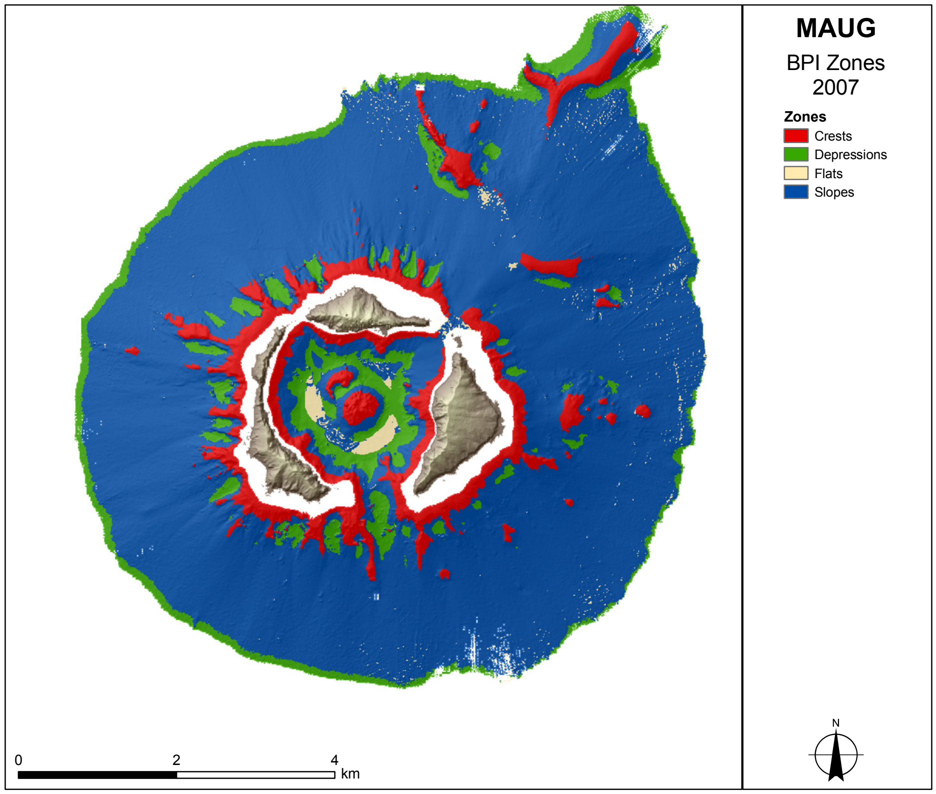


Figure 16.3.1e. BPI zones of 10-m bathymetric grid around Maug derived from data collected in 2007. BPI is a second-order derivative of bathymetry that evaluates elevation differences between a focal point and the mean elevation of the surrounding cells within a user-defined circle. Four BPI Zones—crests, depressions, flats, and slopes—were used in this analysis.

High-resolution Multibeam Backscatter and Derivatives

Backscatter data acquired around Maug were generally of good quality, with coverage to a depth of 250 m, and reveal patterns in the seabed character around Maug (Fig. 16.3.1f) that relate to features in the topography.

Some artifacts were present in the data, such as higher backscatter values recorded within the shallower part of the outer swath versus the deeper part. This can be caused by steep slopes affecting the intensity of the backscatter return. These backscatter data may have been affected by sonar settings and sea state during data acquisition or by other factors discussed in more detail in Chapter 2: "Methods and Operational Background," Section 2.2.2: "Acoustic Mapping: Data Processing.". To exclude these artifacts, the backscatter data were clipped to a depth of 200 m prior to deriving the hard–soft substrate map.

The caldera floor is characterized by very low-intensity backscatter, indicative of soft sediments, and much of this area is classified as soft substrates in the hard–soft map. Similarly, backscatter values are low within the channel between East and West Islands, suggesting that the soft sediments characteristic of the caldera floor continue through this channel. In contrast, the twin peaks of the central dome have much higher backscatter values and are characterized as hard substrates (Fig. 16.3.1g).

Areas along the inner crater wall, with predominantly high backscatter values, are classified as hard substrates. The shallow outer flanks and ridges are classified as hard substrates, but, in the channels between these ridges, some low backscatter values suggest soft substrates.

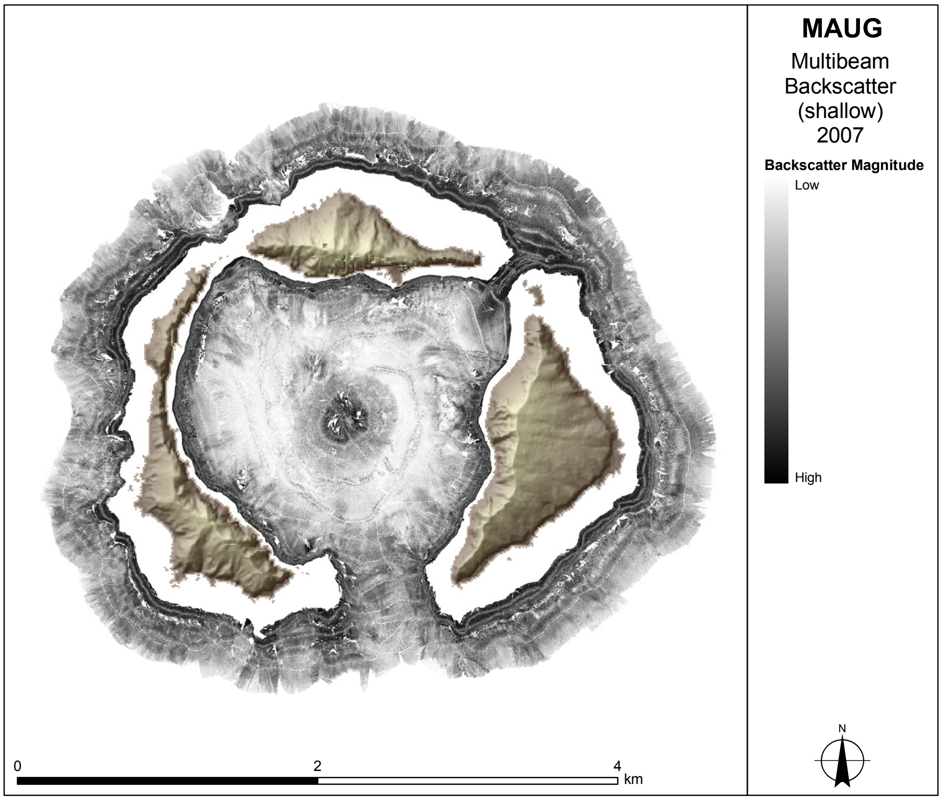


Figure 16.3.1f. Gridded, high-resolution, multibeam backscatter data (grid cell size: 1 m) collected around Maug during MARAMP 2007. Light shades represent low-intensity backscatter and may indicate acoustically absorbent substrates. Dark shades represent high-intensity backscatter and may indicate consolidated hard-bottom and coral substrates.

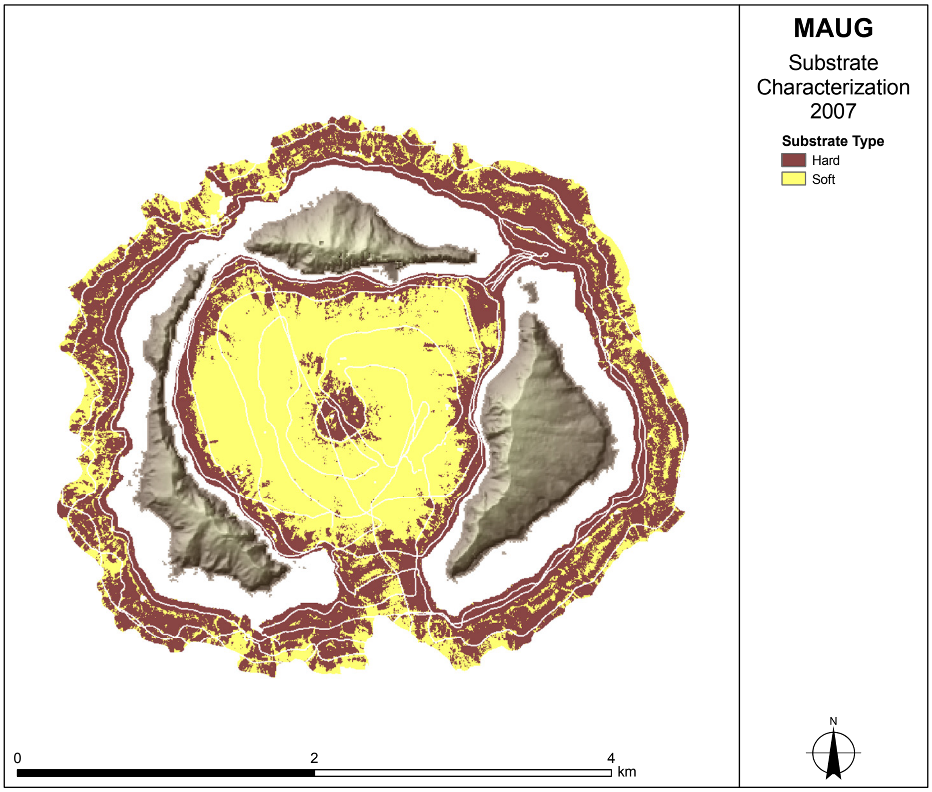


Figure 16.3.1g. Hard and soft substrates (grid cell size: 5 m) at depths < 200 m based upon an unsupervised classification of multibeam bathymetry and backscatter data around Maug in 2007. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

16.3.2 Optical Validation

During MARAMP 2003, 6 TOAD optical-validation surveys were conducted around Maug at depths of ~ 20–225 m (Fig. 16.3.2a). Subsequent analyses of video acquired from these surveys provided estimates of the percentages of sand cover and live-hard-coral cover.

Covering a distance of 76 km at depths of ~ 3–25 m, 40 towed-diver optical-validation surveys of forereef habitats were conducted around Maug during MARAMP 2003, 2005, and 2007. At 5-min intervals within each survey, divers recorded percentages of sand cover and live-hard-coral cover as well as habitat complexity using a 6-level categorical scale from low to very high.

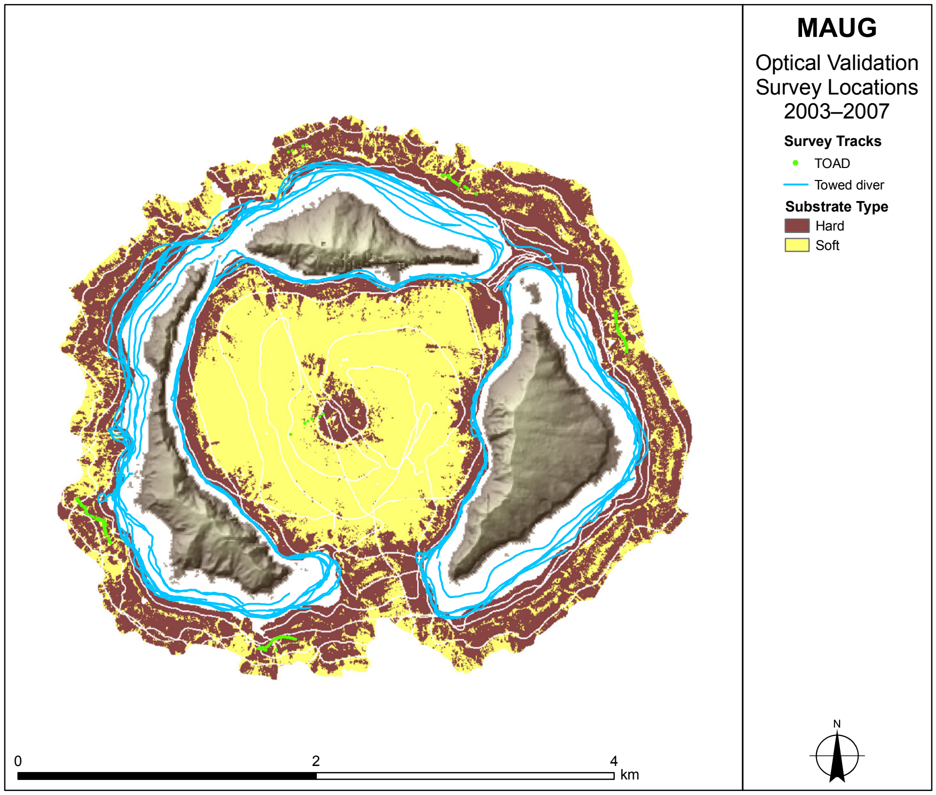


Figure 16.3.2a. Towed-diver tracks from surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007, and TOAD camera-sled tracks for MARAMP 2003. Survey tracks are displayed over the multibeam hard–soft substrate map. Data cannot be collected directly under the ship, hence the white lines showing the ship's path.

16.3.3 Habitat Characterization

Sand cover, habitat complexity, and live coral cover around Maug are discussed in this section. These descriptions are discussed with reference to the 7 geographic regions around Maug.

Towed-diver observations during MARAMP 2003, 2005, and 2007 recorded medium to high habitat complexity through most of the area surveyed, with only 2 moderately sized patches where habitat complexity was lower (Fig. 16.3.3a). These low-complexity areas were on the inner crater edge between North and West Islands near the northwest channel into the caldera and on the inner crater south of the pass between North and East Islands. In both areas, the habitat had predominantly sand and other soft sediment (classified as sand using the towed-diver benthic classification), with sand cover > 75% in places (Fig. 16.3.3b) and live coral cover < 20% (Fig. 16.3.3c).

Based on qualitative observations and photographic data from towed-diver surveys, sand was primarily basalt-derived around Maug; however, sand composition shifted noticeably as divers progressed south of the pass between North and East Islands, changing from basalt-based sand to fine, unconsolidated sediments that were brown, orange, and yellow-tinted, with an increase in particulate suspension of similar color within the water column. These areas of "fluffy" silt appeared to be associated with a hydrothermal vent system, which was documented in the east caldera region near REA site MAU-02 (for the location of REA sites, see Figure 16.2a in Section 16.2: "Survey Effort"). In 2007, water samples, gas bubbles, and temperatures were collected at this vent system near CTD cast 17 (for the location of this nearshore cast, see Figure 16.4.1f in Section 16.4: Oceanography and Water Quality”). A second hydrothermal site was noted near the middle of the northern caldera slope west of MAU-06, with divers noting decreased water visibility, yellow sediment intermixed with basaltic sand, increased benthic substrate temperature (hot sand), and increased water temperature.

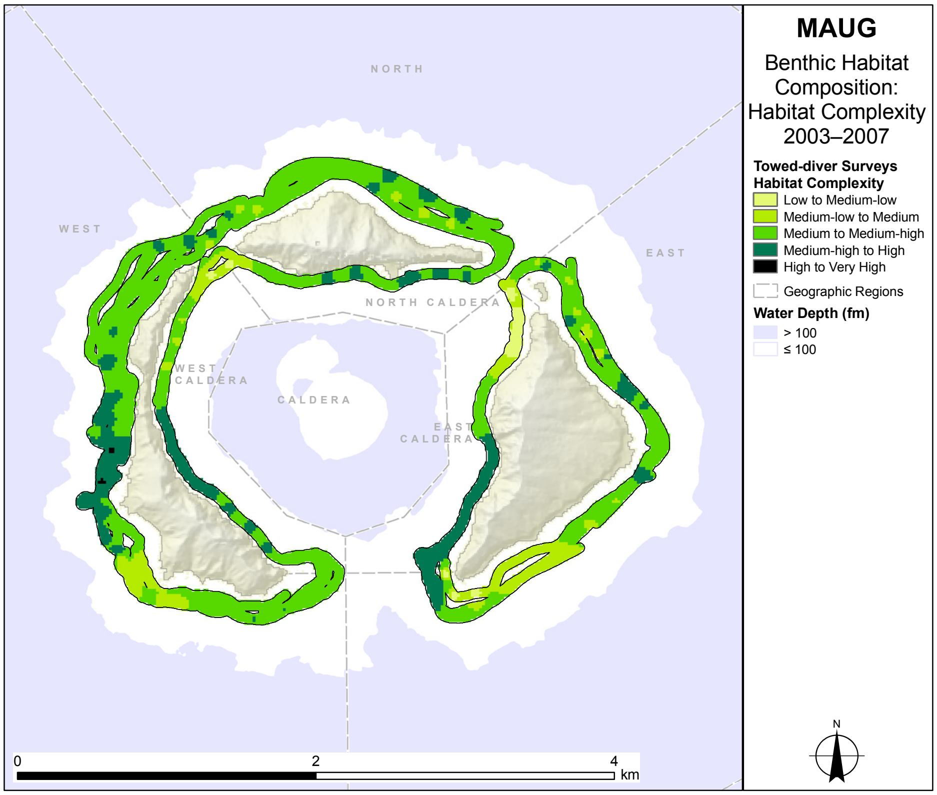


Figure 16.3.3a. Observations of benthic habitat complexity from towed-diver survey of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007.

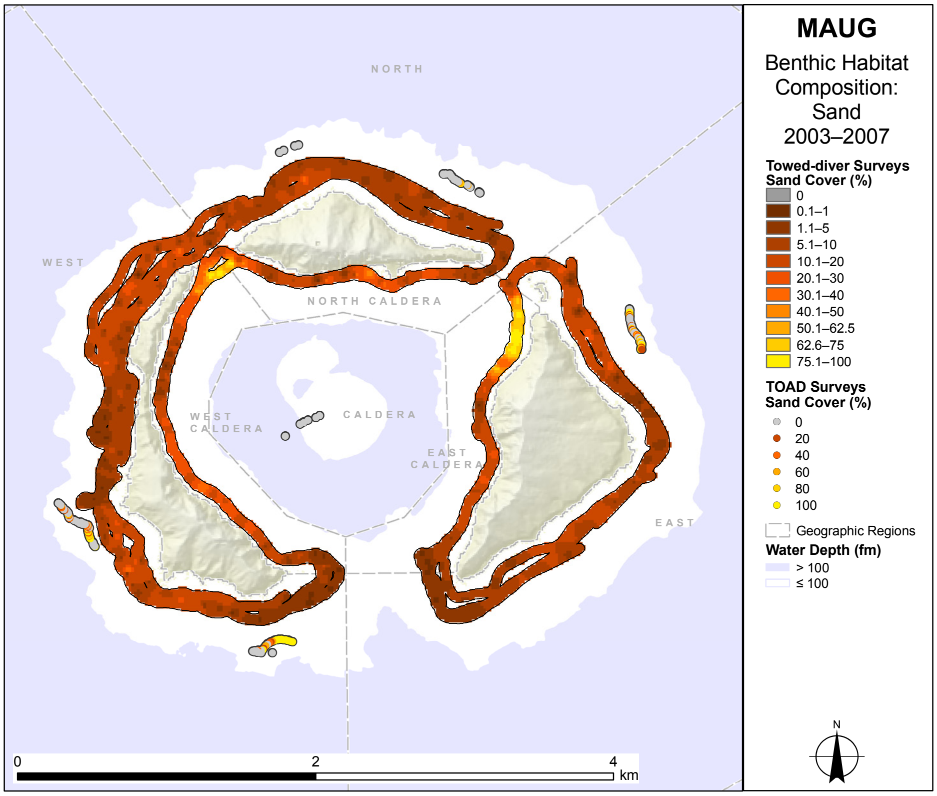


Figure 16.3.3b. Observations of sand cover (%) from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Maug during MARAMP 2003, 2005, and 2007.

Throughout the MARAMP survey years, sand cover around Maug was low, with the exception of the 2 previously described areas of low complexity where sand cover was high. Sand cover was 20% on the outer flanks and < 30% within the caldera. Analyses of TOAD video acquired in deep waters around Maug suggest that sand cover was patchy. The distribution of sand in these areas appears related to the ridge and channel topography with sand accumulating in channels between the ridges; however, the resolution of the data is insufficient to be highly confident in this hypothesis.

Live coral cover recorded during towed-diver surveys was predominantly > 20%. Areas of lower coral cover included the 2 sandy areas previously described and 2 areas with habitat of medium-low to medium complexity observed south of West Island in the west region and south of East Island in the east region close to the southern entrance into the lagoon. In these 4 locations, live coral cover was < 20%. The highest levels of live coral cover were recorded by towed divers in the west region, where live coral cover > 40% was observed, and in the west caldera region, where interpolated live coral cover for a smaller patch was > 50%. Around the 3 islands, towed divers observed habitats of continuous reef, spur-and-groove reef, and boulder fields.

Although towed-diver surveys in shallow waters found abundant coral habitats, very few live corals were recorded in the deeper waters surveyed using the TOAD. Live coral cover was observed in video footage from only 1 of the 5 TOAD surveys conducted on the outer flanks. Completed off West Island, this survey recorded live coral cover in 2 video frames at a depth of 30 m and 2 video frames at a depth of 80 m. Another survey was conducted over the central dome, but the steep slopes made surveying difficult and only 2 video frames could be fully classified. Live corals were observed in 1 of these video frames at a depth of ~ 160 m.

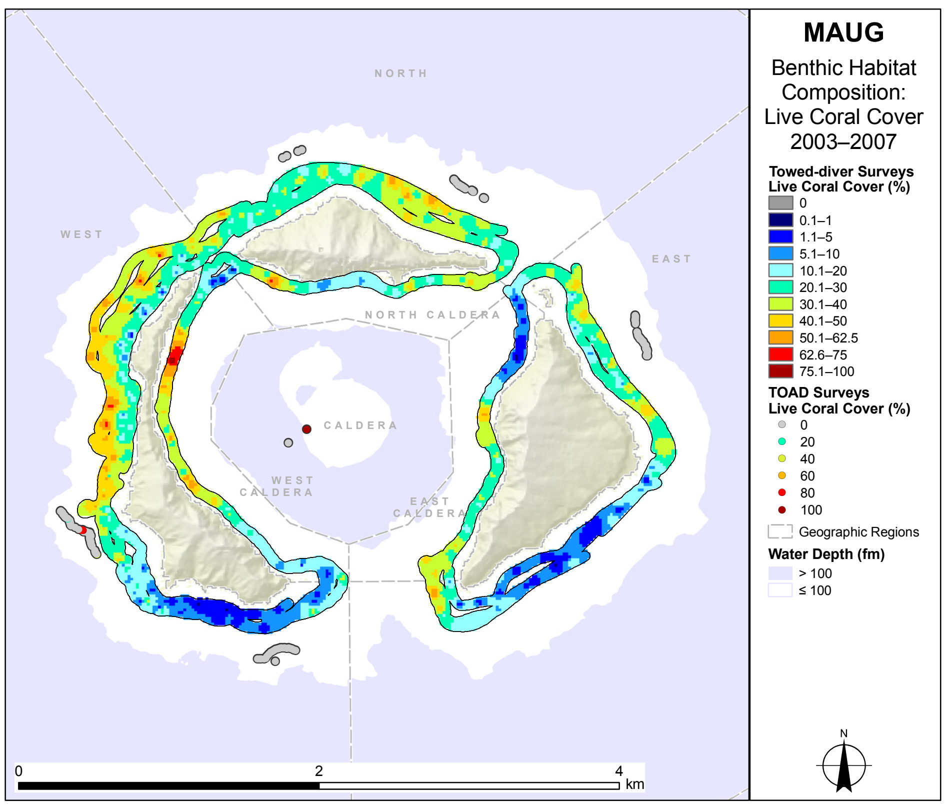


Figure 16.3.3c. Cover (%) observations of live hard corals from towed-diver surveys of forereef habitats conducted and analysis of TOAD video collected around Maug during MARAMP 2003, 2005, and 2007.

16.4 Oceanography and Water Quality

16.4.1 Hydrographic Data

2003 Spatial Surveys

During MARAMP 2003, shallow-water conductivity, temperature, and depth (CTD) casts were conducted in nearshore waters around the islands of Maug over the period of September 2–4. Data from 32 of these casts show that temperature, salinity, density, and beam transmission values varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability (Fig. 16.4.1a). Salinity ranges were small (0.11 psu); however, a clear pattern of higher salinity inside the caldera, compared to the outer regions, was present. The highest temperature (30.19°C) and lowest beam transmission (93.07%) values at Maug were also recorded inside the caldera (cast 24), principally owing to the warm and turbid water located at a hydrothermal vent system west of East Island (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). More information on this vent system is provided later in the "2007 Spatial Surveys" discussion. Vertical comparisons of CTD profiles (Fig. 16.4.1b) reveal a broad range in temperature (1.7°C) that was likely a result of the cooler water (28.5°C) intrusions observed below the depth of 23 m in the north and east regions (casts 10–12). In general, data show mostly well-mixed, homogenous waters around Maug; however, salinity values were distinctly higher inside the caldera regions (casts 17–32) than in the outer regions (casts 1–16). Beam transmission values were lower and density values were higher on the inside of Maug than on the outside.

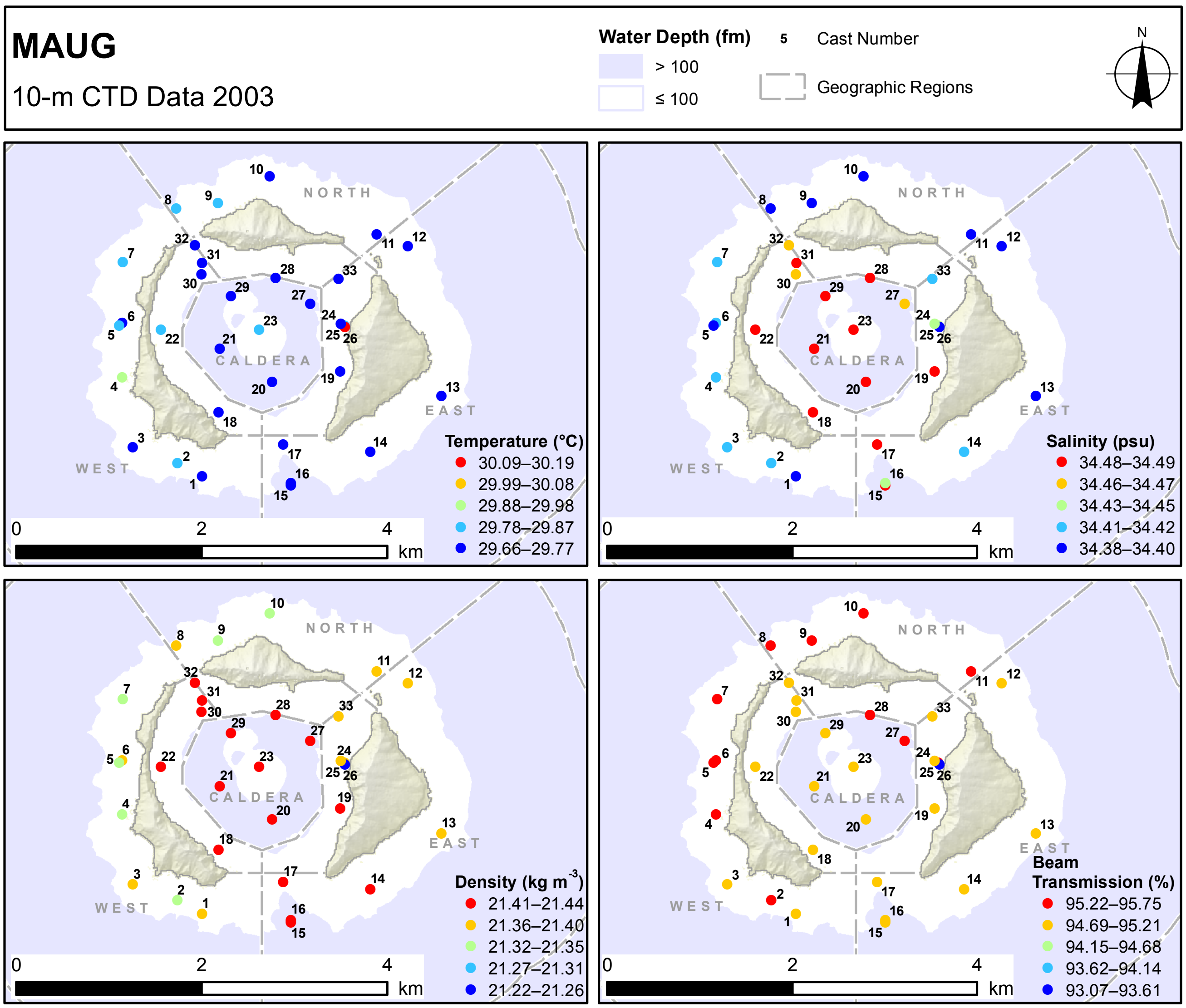
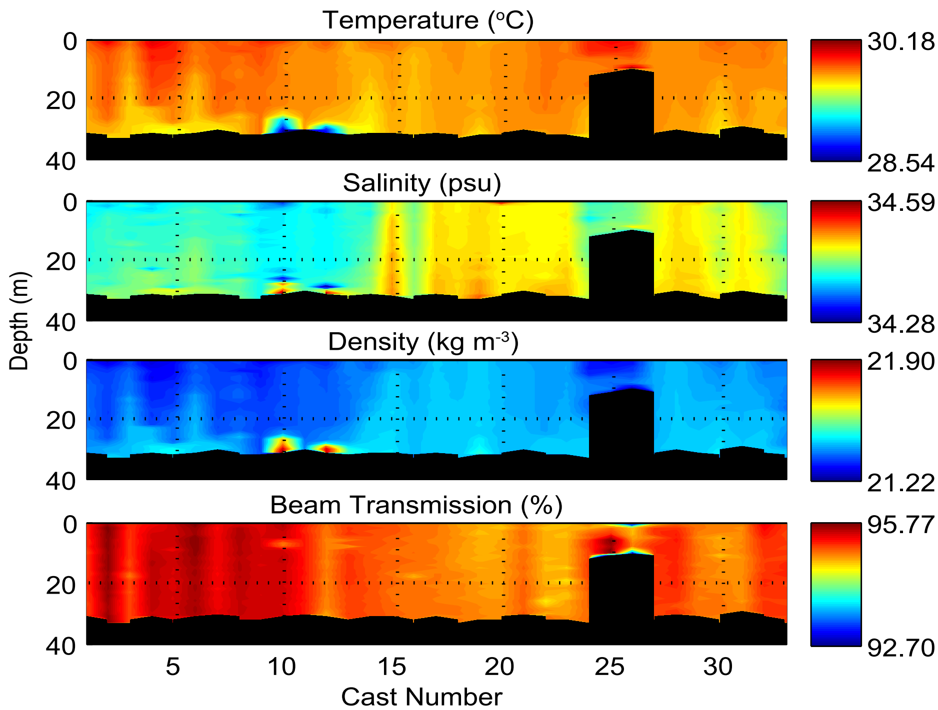


Figure 16.4.1a. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Maug on September 2–4 during MARAMP 2003.

Figure 16.4.1b. Shallow-water CTD cast profiles to a 30-m depth around Maug on September 2–4 during MARAMP 2003, including temperature (°C), salinity (psu), density (kg m-3), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–32, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2003, see Figure 16.4.1a.



2005 Spatial Surveys

During MARAMP 2005, shallow-water CTD casts were conducted in nearshore waters around Maug over the period of September 11–13. Data from 31 of these casts show that waters varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest low variability in temperature (0.15°C), salinity (0.07 psu), density (0.09 kg m^{-3}), and beam transmission (0.99%); however, waters were slightly cooler and more saline in the regions outside of Maug than in the caldera regions (Fig. 16.4.1c). Vertical comparisons of CTD profiles reveal a highly stratified water column with a large range in temperature (1.2°C) values accompanied by moderate ranges in salinity (0.3 psu), density (0.5 kg m^{-3}), and beam transmission (2.8%) values (Fig. 16.4.1d). In general, surface temperatures in the outer regions were similar to values found in the caldera regions, but cooler (~ 0.5°C) temperatures were observed below the depth of 5 m in the outer regions. Differences in salinity and density values show a marked correspondence with differences in temperature values.

Water samples were collected in concert with shallow-water CTD casts at select locations around Maug in 2005 to assess water-quality conditions. The following ranges of measured parameters were recorded: chlorophyll-*a* (Chl-*a*), 0.09–1.20 µg L^{-1}; total nitrogen (TN), 0.04–0.25 µM; nitrate (NO_3^-), 0.02–0.23 µM; nitrite (NO_2^-), 0.010–0.032 µM; phosphate (PO_4^{3-}), 0.006–0.034 µM; and silicate [$Si(OH)_4$], 0.70–1.31 µM. Based on data from 13 sample locations, total nitrogen and nitrate concentrations were all higher in the outer regions versus the caldera regions, whereas nitrite, phosphate, and silicate values showed the opposite spatial pattern (Fig. 16.4.1e). Chl-*a* levels at Maug were consistently lower inside of the caldera than outside, where Chl-*a* concentrations were higher in the east and west regions than just outside the north region. Total nitrogen and nitrate followed a similar pattern except that values were low in the west region compared to the other outer regions.

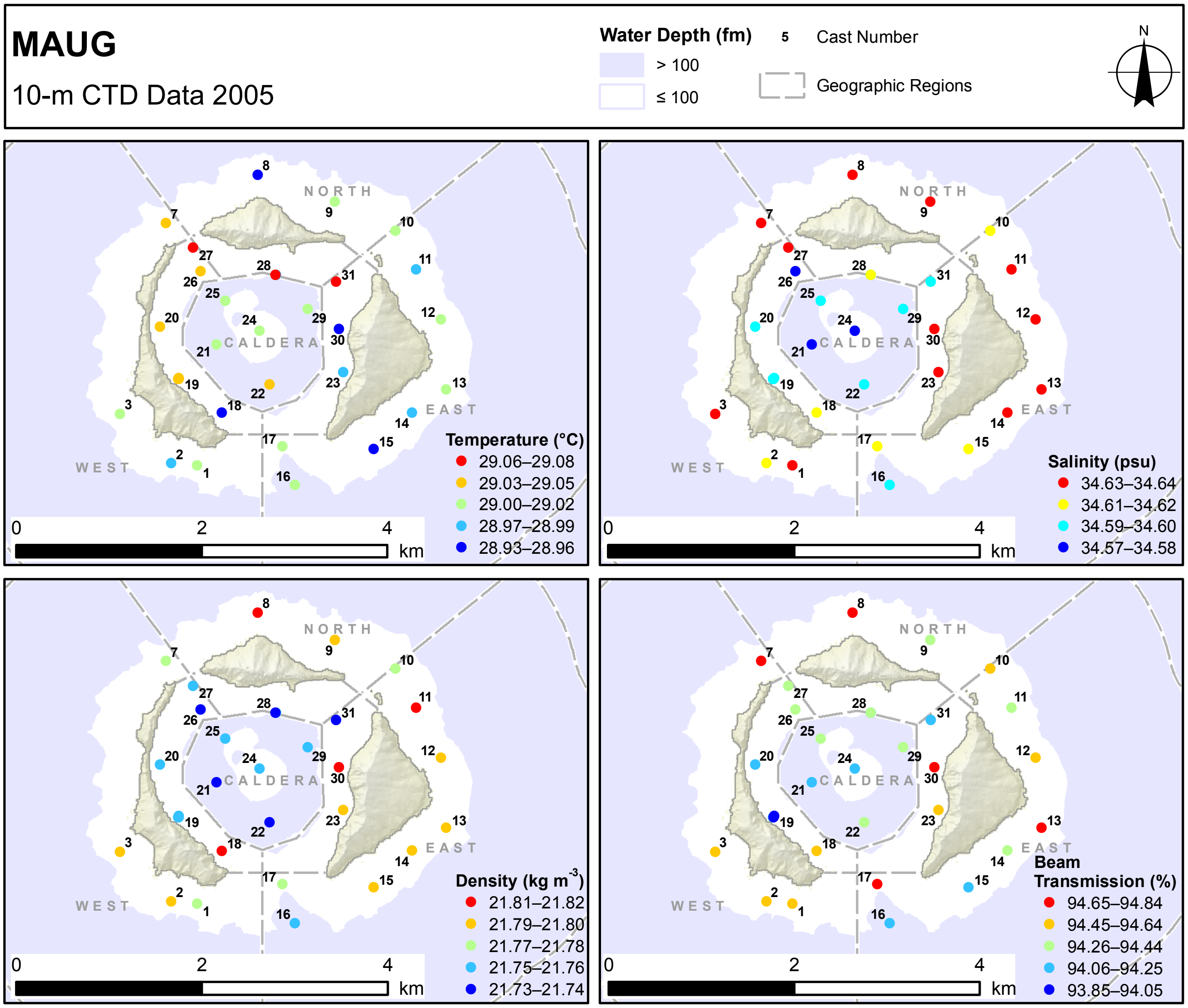
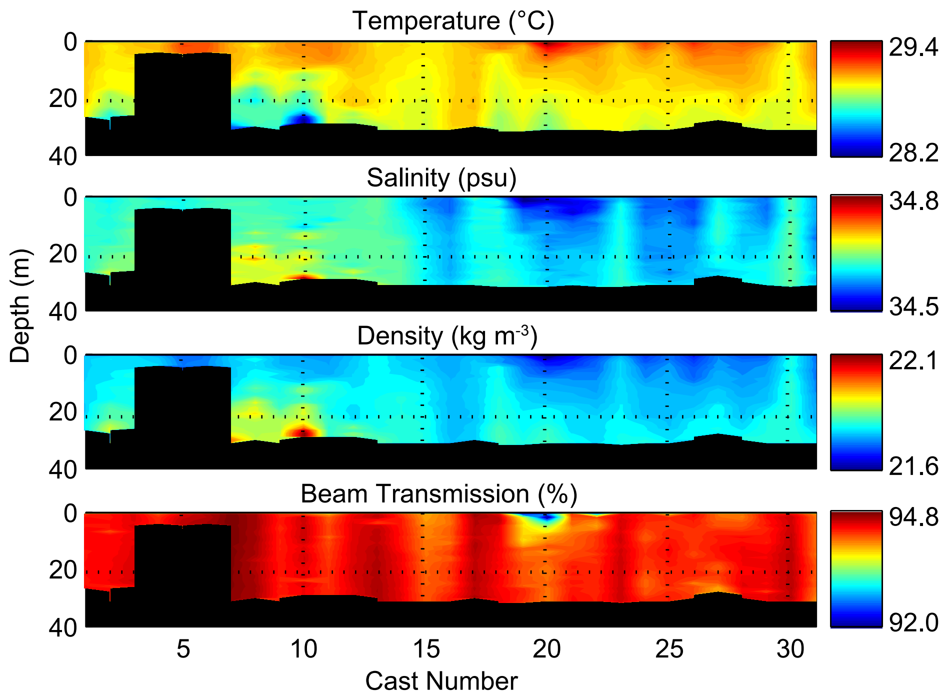


Figure 16.4.1c. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, and (*bottom right*) beam transmission at a 10-m depth from shallow-water CTD casts around Maug on September 11–13 during MARAMP 2005. Data for casts 4–6 are not presented in this map because those casts did not go down to a depth of 10 m.

Figure 16.4.1d. Shallow-water CTD cast profiles to a 30-m depth around Maug on September 11–13 during MARAMP 2005, including temperature (°C), salinity (psu), density (kg m-3), and beam transmission (%).Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–31, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2005, see Figure 16.4.1c.



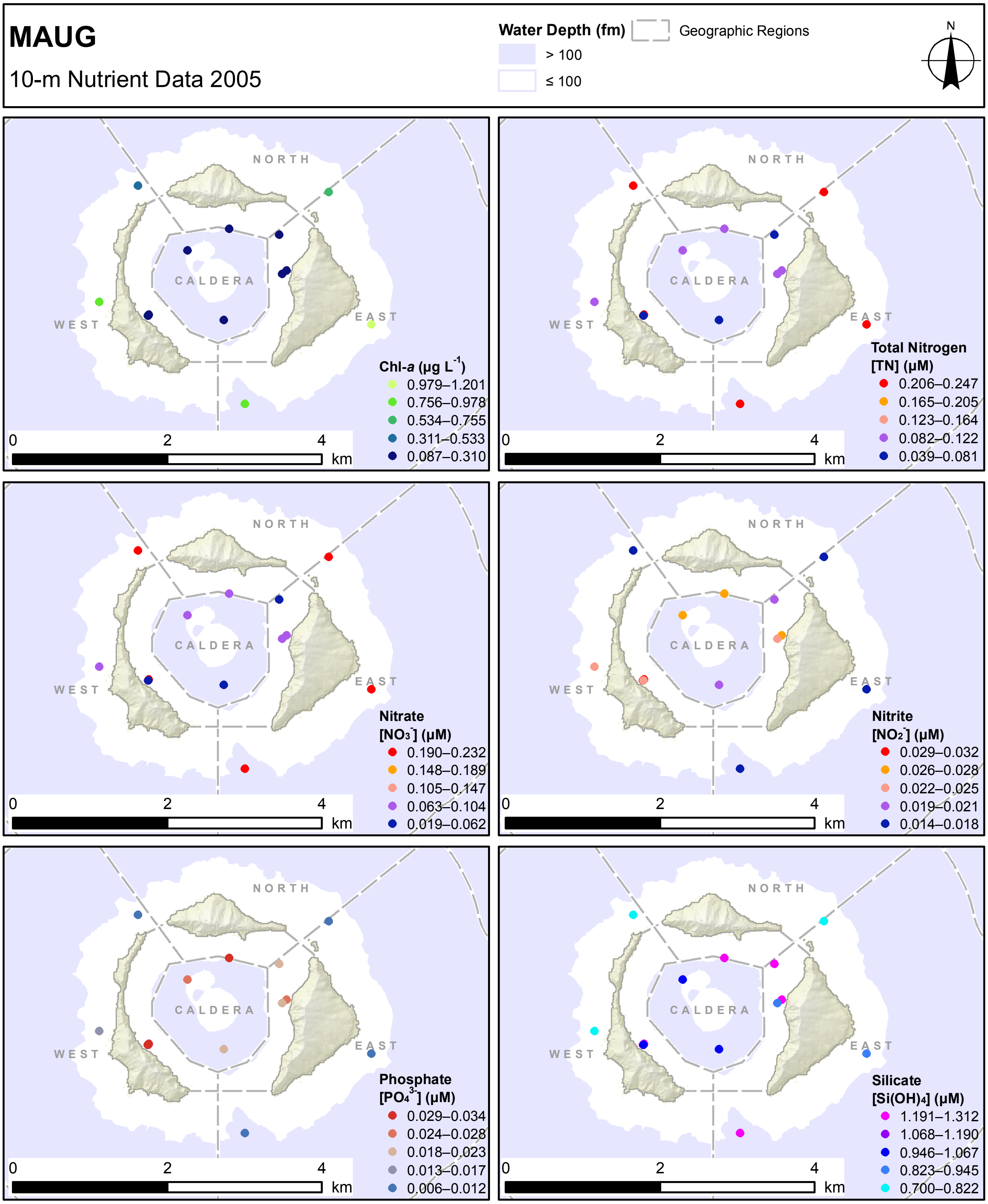


Figure 16.4.1e. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected in concert with shallow-water CTD casts around Maug on September 11–13 during MARAMP 2005.

2007 Spatial Surveys

During MARAMP 2007, 20 shallow-water CTD casts were conducted in nearshore waters around Maug over the period of May 30–June 1. Temperature, salinity, density, and beam transmission values from these casts varied both spatially and vertically around these islands. Spatial comparisons of water properties at a depth of 10 m suggest moderate variability in temperature (0.68°C) values, with low variability in salinity (0.04 psu), density (0.23 kg m^{-3}), and beam transmission (0.94%) values (Fig. 16.4.1f). Vertical comparisons of CTD profiles from Maug reveal water properties with considerable ranges in temperature (3.7°C) and density (1.2 kg m^{-3}) values and moderate ranges in salinity (0.4 psu) and beam transmission (3.7%) values (Fig. 16.4.1g). This range in temperature can be attributed to local upwelling of subsurface waters below the depth of 15 m on the outside of these islands. The physical mechanism driving this upwelling is unknown; however, the subsurface temperature data obtained from a depth of 10 m at Maug, and presented later in Section 16.4.2: "Time-series Observations" (Fig 16.4.2d, mooring site MAU-003), show high-frequency temperature fluctuations of 1°C–3°C, suggesting internal tide activity.

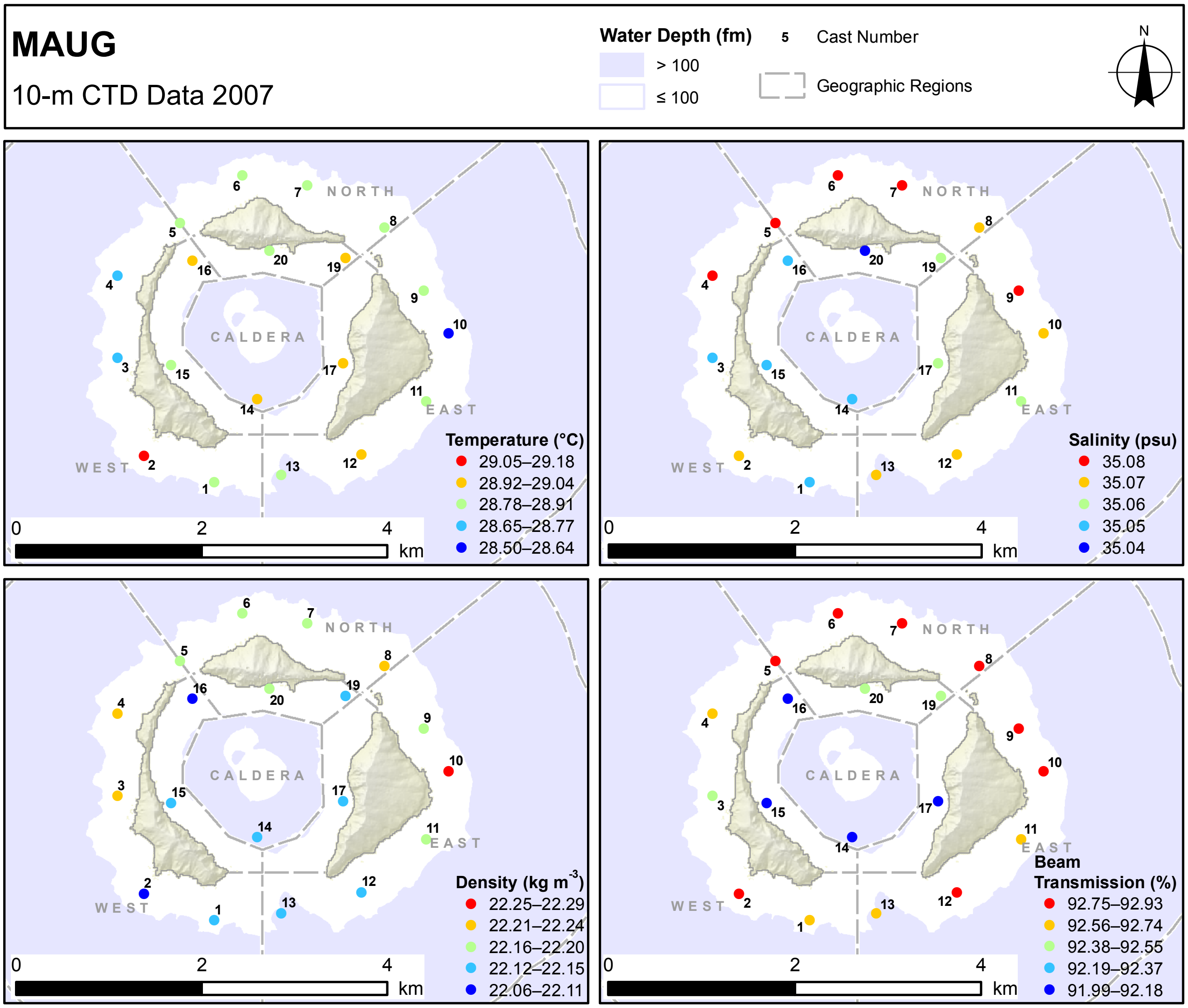


Figure 16.4.1f. Values of (*top left*) water temperature, (*top right*) salinity, (*bottom left*) density, (*bottom right*) and beam transmission at a 10-m depth from shallow-water CTD casts around Maug on May 30–June 1 during MARAMP 2007. Data for cast 18 are not presented in this map because that cast did not go down to a depth of 10 m.

Water samples were collected in concert with shallow-water CTD casts at 9 select locations around Maug in 2007 to assess water-quality conditions. The following ranges of measured parameters were recorded: Chl-*a*, 0.04–0.18 µg/L; total nitrogen (TN), 0.001–0.092 µM; nitrate (NO_3^-), 0.001–0.084 µM; nitrite (NO_2^-), 0–0.010 µM; phosphate (PO_4^{3-}), 0.001–0.010 µM; and silicate [$Si(OH)_4$], 1.15–1.96 µM. All measured parameters, except silicate, were generally observed at the relatively low levels typical of the Western Pacific Warm Pool's oligotrophic, oceanic surface layers. The highest values of silicate were recorded inside the caldera at Maug, while values in the outer regions were relatively homogenous (Fig. 16.4.1h). Also, Chl-*a* values were higher inside than outside the caldera.

A survey was performed during MARAMP 2007 at a single site (cast 17) at the hydrothermal vent system located in the caldera west of East Island. The purpose of this survey was to collect and analyze area-wide and near-vent water samples to gain insight into the marine geochemistry of hydrothermal vents in the CNMI and the possible influences of this specific vent system on the surrounding benthic ecosystem. Divers collected gas bubbles for analyses of carbon dioxide (CO_2) and hydrogen sulfide (H_2S) concentrations, water samples for dissolved inorganic carbon (DIC), total alkalinity (TA), pH, iron, manganese, trace metal, and nutrient concentrations, and temperatures from multiple locations within this vent site. Temperatures near this vent system, measured with a hand-held thermometer, ranged from 45°C to 63°C, levels that were 16°C–34°C above ambient water temperatures. Preliminary analyses of water samples collected at this vent site found pH as low as 6.07, TA of 3.56, and aragonite saturation state of 0.25 (D Butterfield, pers. comm.), suggesting a highly corrosive environment at this vent system.

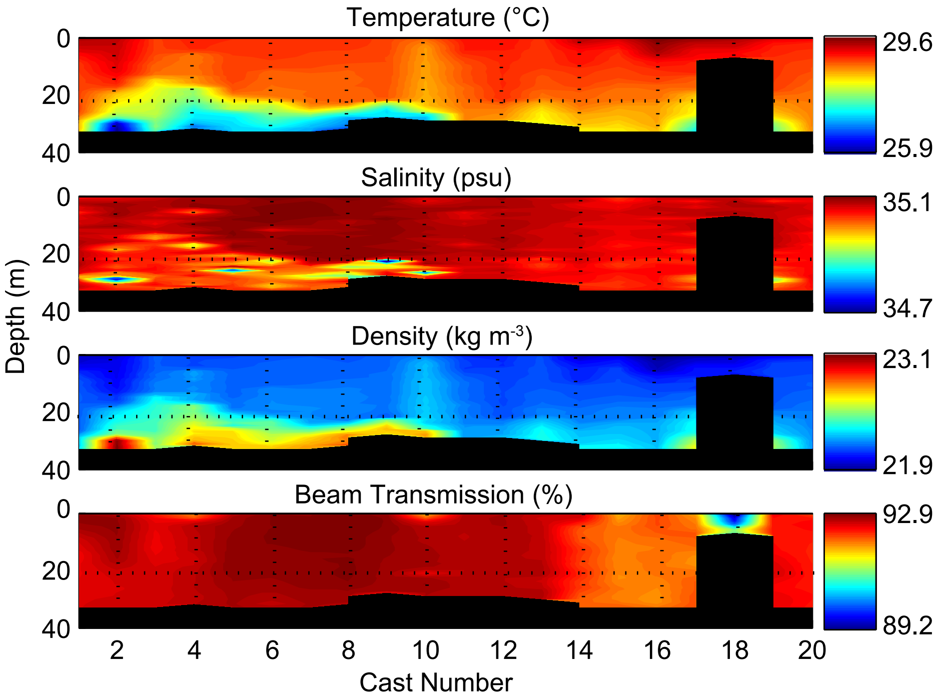


Figure 16.4.1g. Shallow-water CTD cast profiles to a 30-m depth around Maug on May 30–June 1 during MARAMP 2007, including temperature (°C), salinity (psu), density (kg m^{-3}), and beam transmission (%). Profiles, shown sequentially in a left-to-right direction in this graph, correspond to cast locations that are numbered sequentially 1–20, in a clockwise direction around Maug. For cast locations and numbers around these islands in 2007, see Figure 16.4.1f.

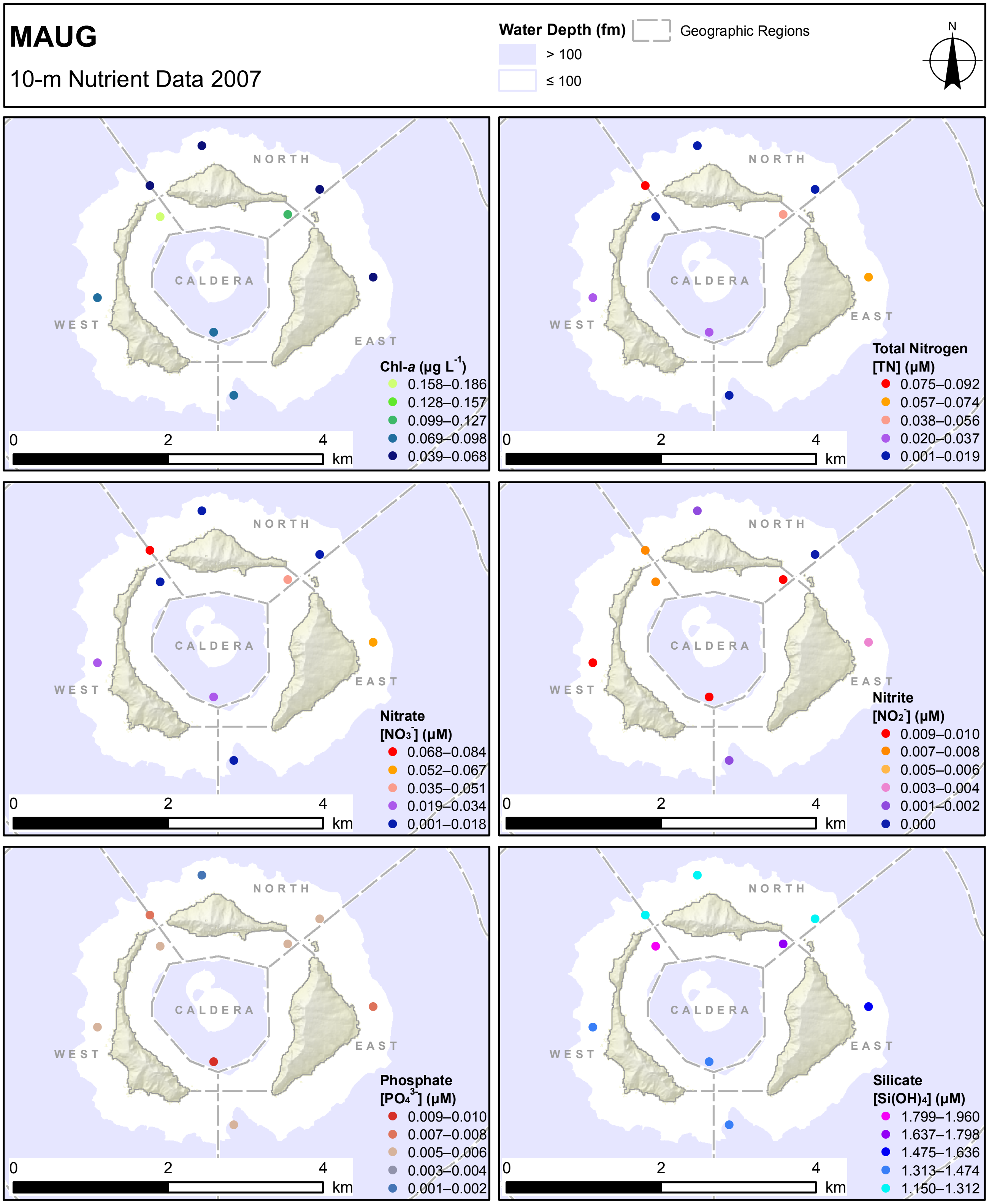


Figure 16.4.1h. Concentrations of (*top left*) Chl-*a*, (*top right*) total nitrogen, (*middle left*) nitrate, (*middle right*) nitrite, (*bottom left*) phosphate, and (*bottom right*) silicate at a 10-m depth, from water samples collected in concert with shallow-water CTD casts around Maug on May 30–June 1 during MARAMP 2007.

Temporal Comparison

Comparisons between survey periods of shallow-water CTD data collected around Maug during MARAMP 2003, 2005, and 2007 suggest a dynamic physical environment. During the first 2 MARAMP survey periods, low spatial variability and moderate vertical structure were observed, yet substantial spatial heterogeneity in physical water properties was found during the third survey period in 2007. Intrusions of cooler (25.9°C) waters in the outer regions were prominent in 2007, likely a result of upwelling or internal tide activity. Data were not collected with respect to a specific tidal cycle, which could be a source of oceanographic variability. Likewise, hydrographic variation between MARAMP survey years is likely a result of differences in season. MARAMP 2007 occurred in May, and MARAMP 2003 and 2005 occurred in September. This change was made to avoid the typhoon season and reduce the probability of weather disruptions. Additionally, differences in salinity values between the caldera regions and the outer regions were prominent in 2003 and 2005; however, data from 2003 show that salinity values were higher inside than outside the caldera at Maug, whereas data from 2005 present the opposite pattern.

Water-quality data obtained during MARAMP 2005 and 2007 suggest that nutrient concentrations were variable spatially between survey years. Values for nearly all of the parameters measured were lower in 2007 than in 2005, particularly Chl-*a* values, which were an order of magnitude lower. Total nitrogen, nitrate, and nitrite values were also notably lower in 2007 than 2005. Whether these differences resulted from a seasonal effect or some other process is unknown at this time. This pattern is seemingly paradoxical given the observed variability in temperature and water movement between 2005 and 2007; however, the water-quality data presented in this report were collected at a depth of 10 m, whereas the cooler water was recorded below the depth of 20 m, and, therefore, no nutrient signal is expected in this depth bin.

16.4.2 Time-series Observations

Between 2003 and 2007, 2 types of moored instruments were deployed at Maug to collect time-series observations of temperature, a key oceanographic parameter. The locations, depths, timeframes, and other details about these deployments are provided in Figures 16.4.2a and b.

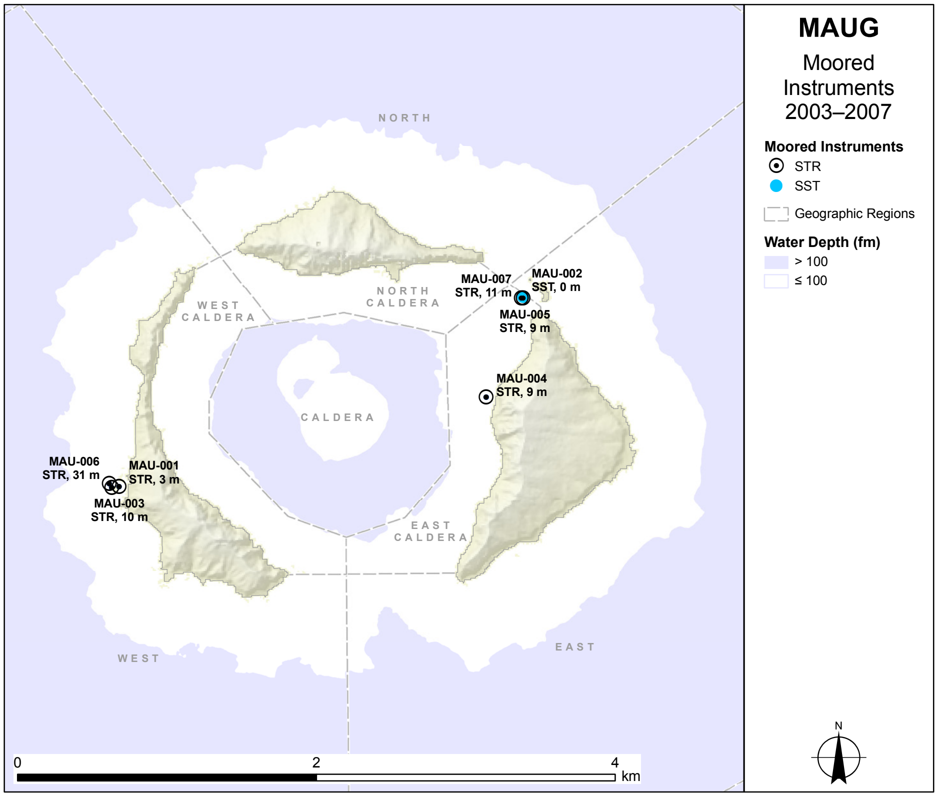
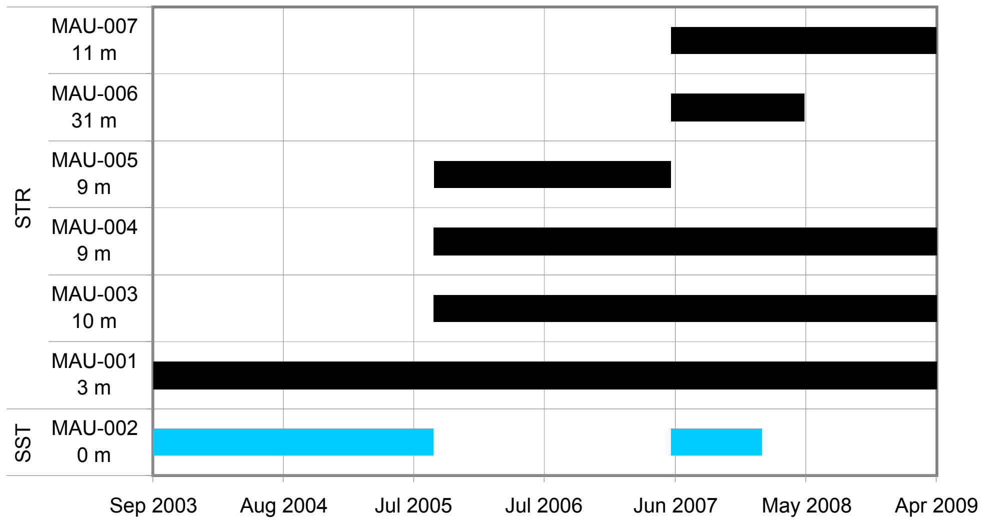


Figure 16.4.2a. Locations, depths, and types of oceanographic instrument moorings deployed at Maug during MARAMP 2003, 2005, and 2007. Two types of instruments were moored at Maug: subsurface temperature recorder (STR) and sea-surface temperature (SST) buoy.

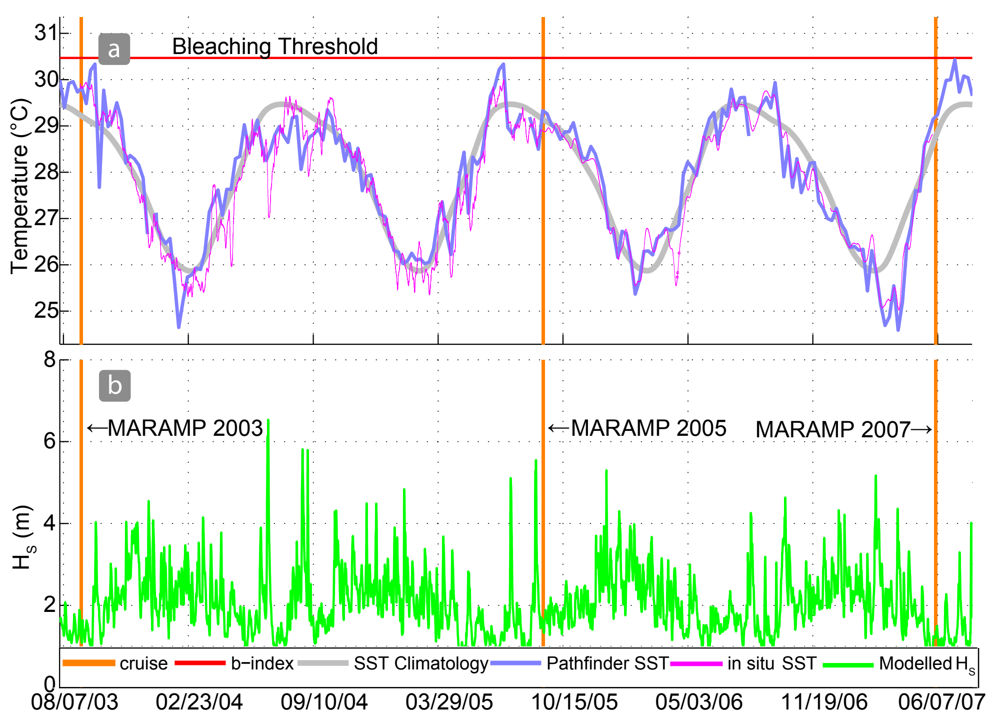
Figure 16.4.2b. Deployment timelines and depths of oceanographic instruments moored at Maug during the period from September 2003 to April 2009. A solid bar indicates the period for which temperature data were collected by a single instrument or a series of them that were deployed and retrieved at a mooring site. For more information about deployments and retrievals, see Table 16.2a in Section 16.2: "Survey Effort." The time periods shown in this figure for data stored on and collected from buoys may differ from the period for which telemetered SST data, shown in Figure 16.4.2c, were available.



Satellite-derived (Pathfinder) sea-surface temperature (SST) and in situ temperature observations around Maug reveal that the seasonal maxima for water temperatures around Maug were typically reached in late August or September. The monthly maximum climatological mean from Pathfinder SST was 29.5°C (Fig. 16.4.2c[a]). Winter minima occurred in February with a monthly minimum climatological mean of 25.9°C. In the winters of 2004 and 2007, Pathfinder SST observations were 1°C cooler than the climatological mean. In general, Pathfinder SST matched SST in situ observations; however, on a number of occasions, including in April 2006, in situ temperatures dropped 0.5°C–1°C below temperatures from Pathfinder data, suggesting a local cooling event not observed in the satellite record. It's important to note that Pathfinder SST represents the upper few millimeters of oceanographic temperatures within the region of an island, as opposed to site- or reef-specific temperatures.

Periods of elevated mean wave heights of 3–4 m were usually more frequent during winter (Fig. 16.4.2c[b]). The largest episodic events of wave heights > 4 m, however, tended to happen during periods of warm temperatures. Warm temperatures typically occur during the period of August–December, when wave heights of > 4 m are generally associated with typhoons. This pattern was especially noticeable during the summer of 2004 with the passages of Typhoons Tingting and Chaba.

Figure 16.4.2c. Time-series observations of (a) SST and (b) wave height around Maug for the period between August 2003 and June 2007. Remotely sensed data (SST climatology and weekly Pathfinder-derived SST) and modeled significant wave height (HS) derived from Wave Watch III are shown with CRED in situ temperature data from SST buoys (see Figure 16.4.2a for buoy locations). The 2 high points in the modeled wave height in the summer of 2004 show the occurrences of Typhoons Tingting and Chaba. The horizontal red and vertical orange bars represent the bleaching threshold and the MARAMP research cruise dates, respectively.



Subsurface temperature recorders (STRs) were deployed at 6 locations at depths of 3–31 m around Maug beginning in September 2003. Data from STRs at 4 of these locations show seasonal temperature variability of 4°C–6°C (Fig. 16.4.2d). Water temperatures reached ~ 31°C during the months of June–October and fell to a low of ~ 25°C during the months of January–May. Temperature at all 4 locations in September 2006 reached the coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean for the region. Temperatures at the shallowest sensor, MAU-001 deployed at a depth of 3 m, exceeded the threshold of 31°C by almost 0.3°C. Diurnal temperature fluctuation was ~ 0.5°C for the shallowest sensor and ~ 0.25°C for the other 3 sensors, which were deployed at depths of 9–10 m. Solar heating and cooling likely caused the fluctuation in diurnal temperature to be greater at MAU-001 than at the other deployments. Additionally, rapid (return periods of 12–24 h) drops of 1°C–3°C in temperature were observed in the spring of 2006 at MAU-003, located on the western side of West Island (outside of the caldera) at a depth of 10 m. Internal tides are generated when tidal currents interact with steep subsurface topography, resulting in high-frequency variability in temperature, salinity, dissolved nutrients, and suspended particle concentrations that differ significantly from shallow reefs to deep slopes. Although more research and additional data are needed to properly ascertain the nature of this signal, the observed rapid temperature changes likely were the result of internal tides causing vertical displacements of the background stratification at MAU-003.

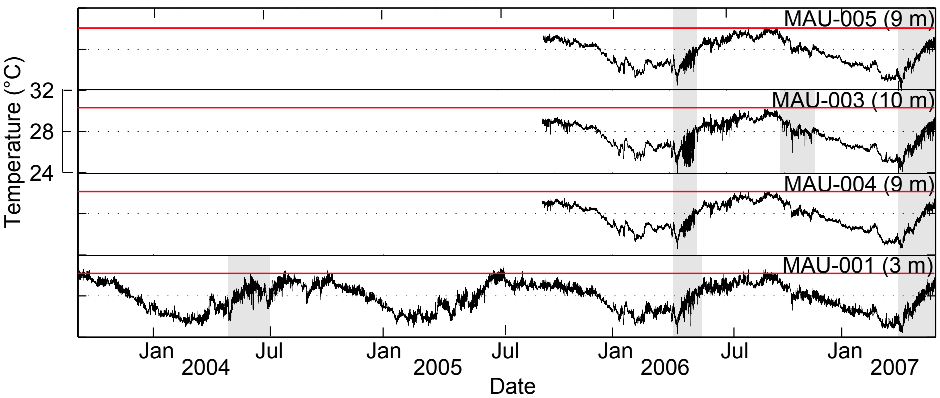


Figure 16.4.2d. Time-series observations of temperature over the period between September 2003 and May 2007 collected from 4 STR mooring sites at different locations and depths at Maug (see Figure 16.4.2a for mooring locations). A grey background indicates a period of high-frequency variability that likely resulted from internal tide activity. The red lines indicate the satellite-derived coral bleaching threshold, which is defined as 1°C above the monthly maximum climatological mean.

16.4.3 Wave Watch III Climatology

Seasonal wave climatology for Maug was derived using the NOAA Wave Watch III model for the period of January 1997 to May 2008 (Fig. 16.4.3a), and seasons were selected to elucidate waves generated by typhoons, which most frequently occur during the period of August–December (for information about the Wave Watch III model, see Chapter 2: “Methods and Operational Background,” Section 2.3.7: “Satellite Remote Sensing and Ocean Modeling”). In terms of consistency, the wave regime during this period was dominated by trade wind swells characterized by frequent (> 30 d per season), relatively short-period (8–10 s), relatively small (2–3 m) wave events originating from the east (90°). Superimposed with these short-period swells were large (> 4 m), long-period (12–16 s) wave events principally from the south (180°), although they could originate from a broad directional source (120°–200°). These large, episodic waves primarily were generated by typhoons and occurred on annual to interannual time scales. Additionally, infrequent (~ 5 d per season), long-period (12–14 s) swells with moderate wave heights (2.5–3.5 m) occurred from the west and southwest (210°–250°) and likely were associated with episodic storms. Similar to the wave regime during typhoon season, the wave climate during the period of February–June (outside the typhoon season) was also characterized by frequent (> 30 d per season) and short-period (~ 8 s) trade wind swells with relatively small wave heights (~ 2 m) originating from the east. Infrequent (< 10 d per season) and long-period (12–14 s) swells with slightly larger wave heights (~ 3 m) also occurred during this period and originate from the northwest (330°).

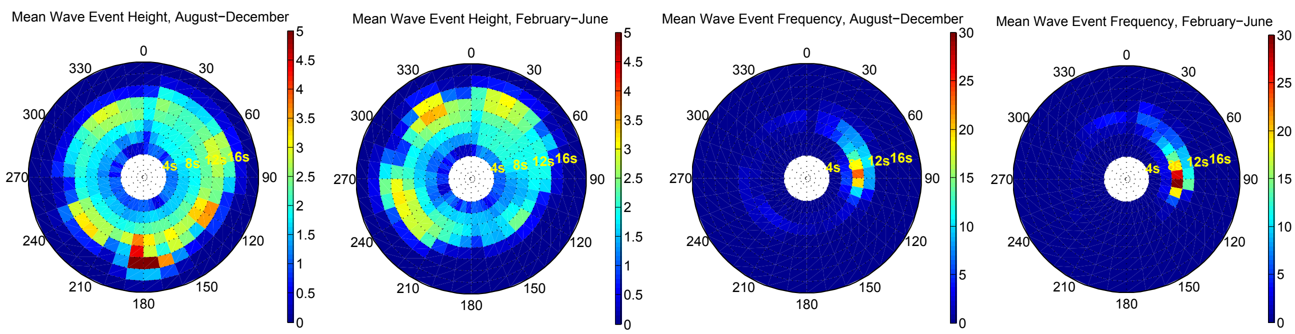


Figure 16.4.3a. NOAA Wave Watch III directional wave climatology for Maug from January 1997 to May 2008. This climatology was created by binning (6 times daily) significant wave height, dominant period, and dominant direction from a box (1° × 1°) centered on Maug (20° N, 144°48′ E). Mean significant wave height (*top*), indicated by color scale, for all observations in each directional and frequency bin from August to December (typhoon season) and from February to June. The transition months of January and July are omitted for clarity. Mean number of days (*bottom*) that conditions in each directional and frequency bin occur in each season, indicated by color scale; for example, if the color indicates 30, then, on average, the condition occurred during 30 of the 150 days of that season.

16.5 Corals and Coral Disease

16.5.1 Coral Surveys

Coral Cover and Colony Density

From MARAMP 2003 towed-diver surveys, mean cover of live hard corals on forereef habitats around the islands of Maug was 27% (SE 1.4). Coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera (Fig. 16.5.1a). Coral cover was highest in the north and west regions. Localized areas of high coral cover were observed in the west caldera region with means in a range of 75.1%–100%.

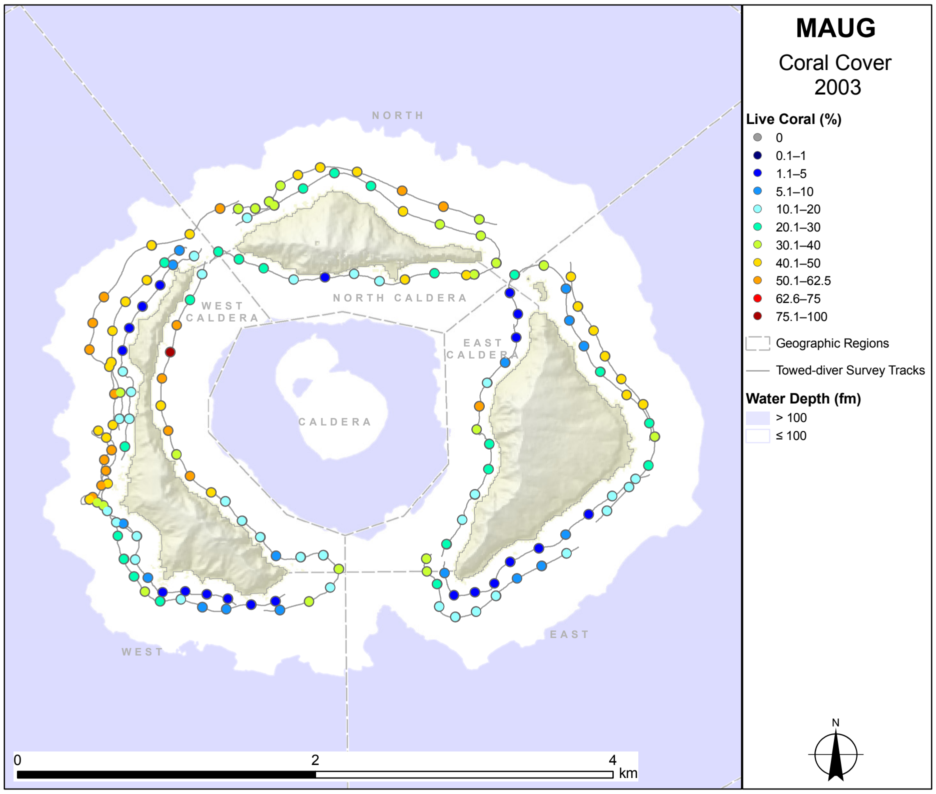


Figure 16.5.1a. Cover (%) observations of live hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²).

During MARAMP 2003, 8 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 892 coral colonies within a total survey area of 30 m^2. Site-specific colony density ranged from 8.8 to 59.5 colonies m^{-2} with an overall sample mean of 29.7 colonies m^{-2} (SE 5.9). The highest colony density was recorded at MAU-03 in the east caldera region, and the lowest colony density was observed in the east region at MAU-04 (Fig. 16.5.1b).

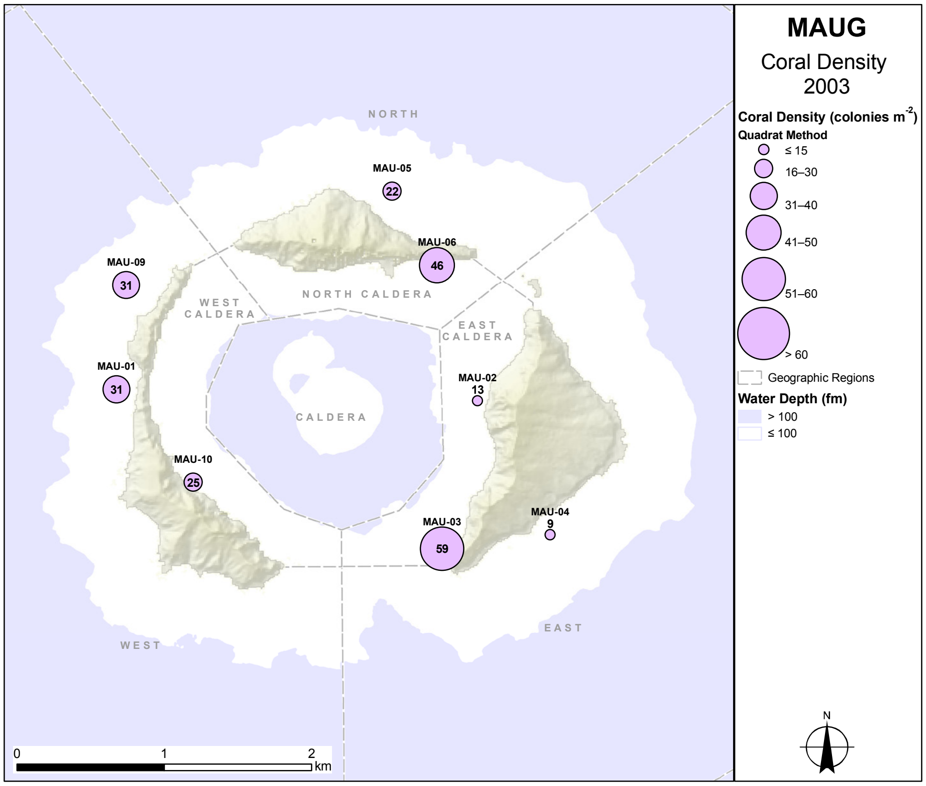


Figure 16.5.1b. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. Values are provided within or above each symbol. The quadrat method was used in 2003 to assess coral-colony density.

From MARAMP 2005 towed-diver surveys, mean cover of live hard corals on forereef habitats around Maug was 21% (SE 1.7). As seen in surveys in 2003, coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera (Fig. 16.5.1c). Coral cover was variable in all other regions with localized areas of relatively high mean coral cover along the outer flank in the west region and in the west caldera and east caldera regions.

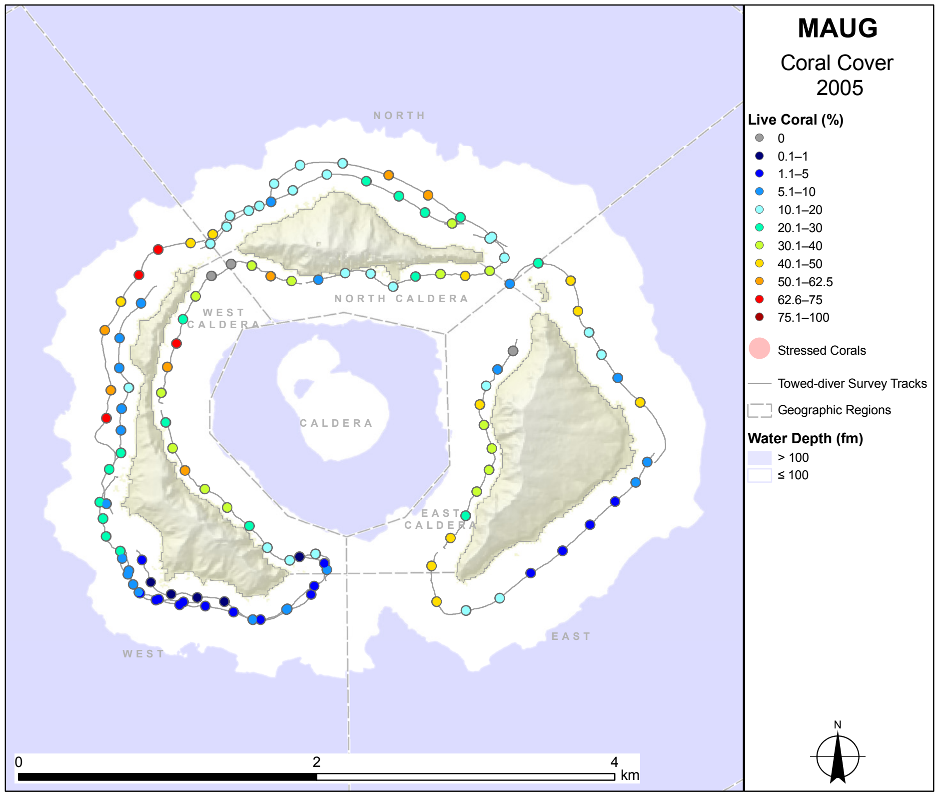


Figure 16.5.1c. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m²). Pink symbols are shown only for segments with stressed-coral cover > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2005.

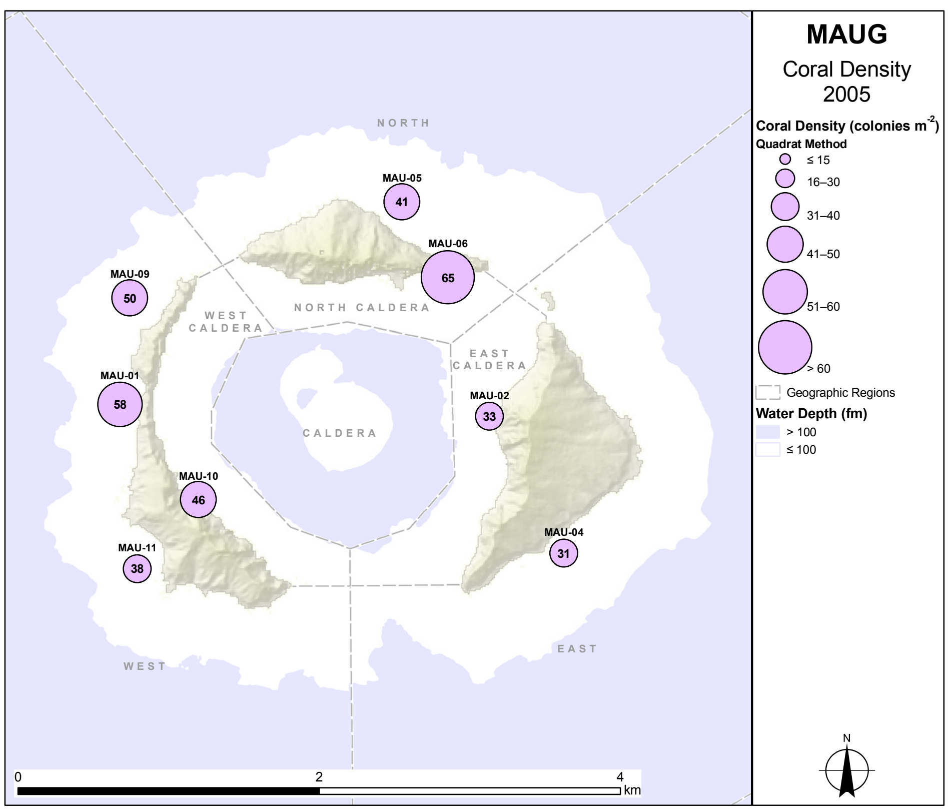


Figure 16.5.1d. Colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. Values are provided within or above each symbol. The quadrat method was used in 2005 to assess coral-colony density.

Towed divers during MARAMP 2005 recorded estimates of stressed-coral cover, including corals that were fully bleached (white), pale or discolored, malformed, or stricken with tumors (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). Overall, 0.5% (SE 0.1) of coral cover observed on forereef habitats around Maug appeared stressed in 2005. The occurrence of stressed-coral cover was low for the majority of forereefs surveyed around Maug in 2005.

During MARAMP 2005, 8 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 1443 coral colonies within a total survey area of 32 m^2. Site-specific colony density ranged from 31 to 64.8 colonies m^{-2} with an overall sample mean of 45.1 colonies m^{-2} (SE 4.2). The highest colony density was recorded at MAU-06 in the north caldera region, and the lowest colony density was observed in the east region at MAU-04 (Fig. 16.5.1d).

From MARAMP 2007 towed-diver surveys, mean cover of live hard corals on forereef habitats around Maug was 26% (SE 1.6). As seen in the previous MARAMP survey years, coral cover was lowest in the east and west regions, adjacent to the southern channel entrance into the caldera. (Fig. 16.5.1e). Coral cover was variable in all other regions with relatively high mean coral cover observed along the outer flanks in the west region. Localized areas of high coral cover were recorded at numerous locations within the caldera, including the southern corner of East Island and isolated locations in the west caldera and north caldera regions (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort").

Overall, 1.4% (SE 1.3) of coral cover observed on forereef habitats around Maug appeared stressed in 2007 (see Chapter 2: "Methods and Operational Background," Section 2.4.5, "Corals and Coral Disease"). The occurrence of stressed-coral cover was low for the majority of forereefs surveyed at Maug. Stressed-coral cover > 10% was observed over 2 segments in the west caldera region and 1 segment in the north caldera region (Fig. 16.5.1e).

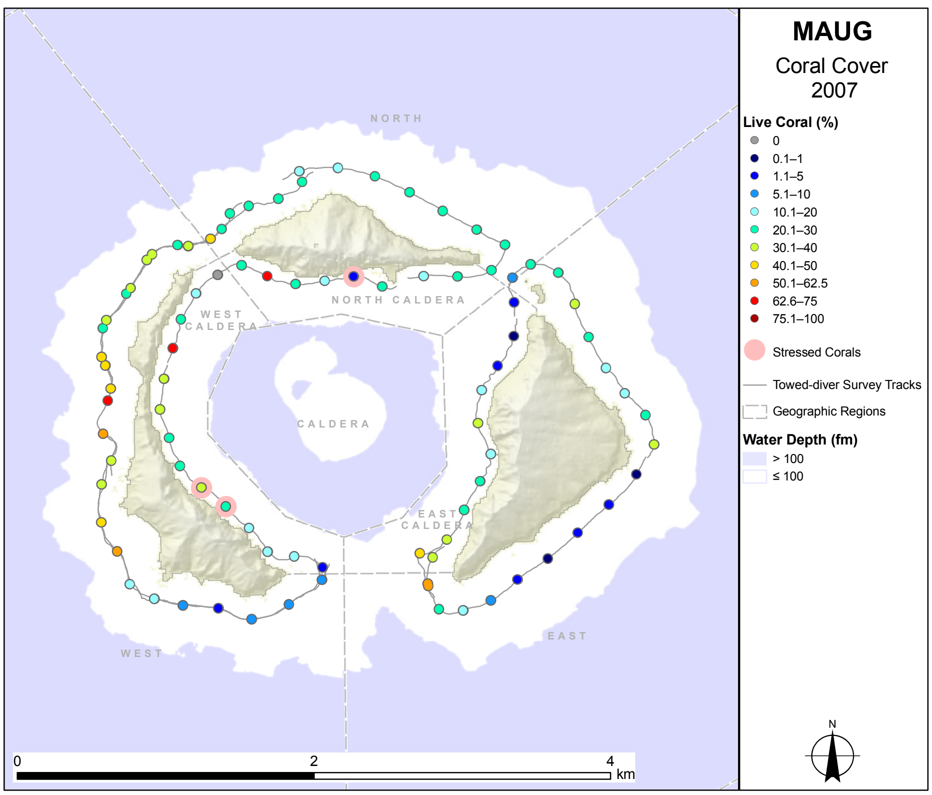


Figure 16.5.1e. Cover (%) observations of live and stressed hard corals from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007. Each colored point represents an estimate of live coral cover over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). Pink symbols represent segments where estimates of stressed-coral cover were > 10%. Stressed-coral cover was measured as a percentage of overall coral cover in 2007.

During MARAMP 2007, 9 REA benthic surveys using the line-point-intercept method were conducted on forereef habitats at Maug. Site-specific estimates of live-hard-coral cover from these surveys ranged from 8.8% to 66.7% with an overall sample mean of 34.1% (SE 5.7). Live coral cover was highest at MAU-02 located near a volcanic vent in the east caldera region and lowest at MAU-04 in the east region (Fig. 16.5.1f).

During MARAMP 2007, 9 REA benthic surveys using the quadrat method on forereef habitats at Maug documented 1699 coral colonies within a total survey area of 36 m^2. Site-specific colony density ranged from 39.5 to 67.3 colonies m^{-2} with an overall sample mean of 47.2 colonies m^{-2} (SE 3). The highest colony density was recorded at MAU-06 in the north caldera region, and the lowest colony density was observed in the east region at MAU-04.

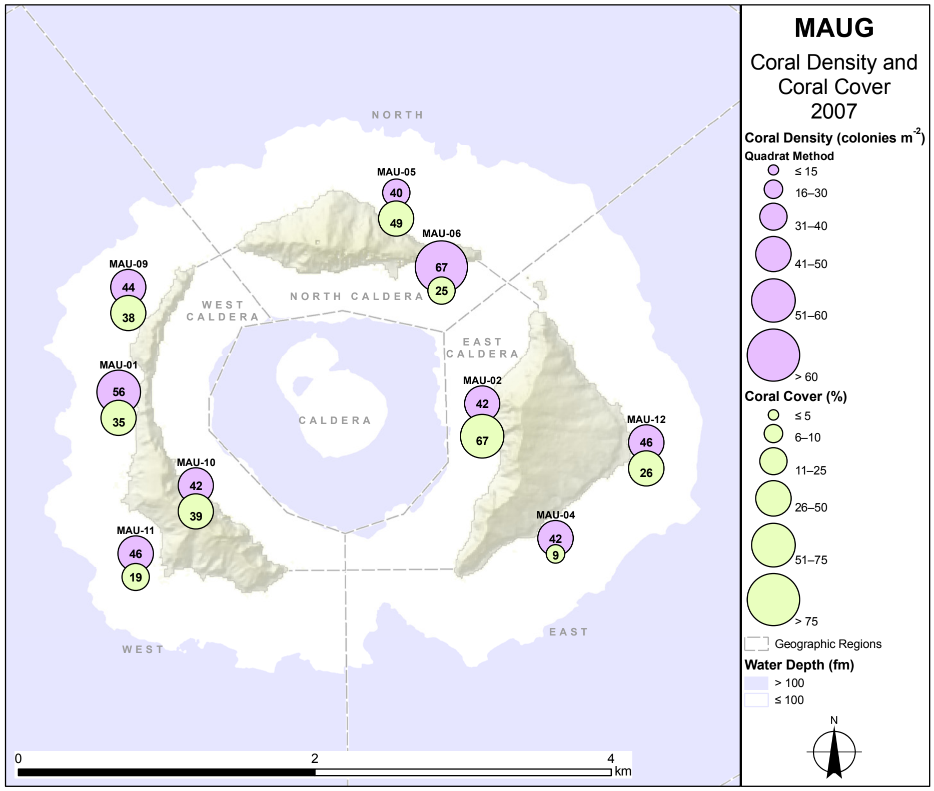


Figure 16.5.1f. Cover (%) and colony-density (colonies m^{-2}) observations of live hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Values are provided within or above each symbol. The quadrat method was used in 2007 to assess coral-colony density.

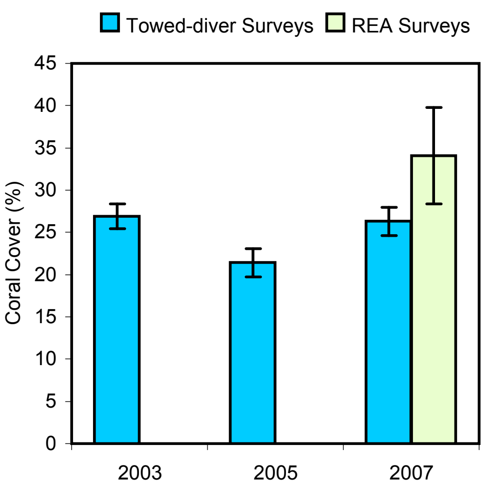


Figure 16.5.1g. Temporal comparison of mean live coral cover (%) values from REA and towed-diver surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. No REA surveys using the line-point-intercept method were conducted around Maug in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Overall mean cover of live corals, estimated from towed-diver surveys of forereef habitats, was 27% (SE 1.4) in 2003, 21% (SE 1.7) in 2005, and 26% (SE 1.6) in 2007 (Fig. 16.5.1g). This relatively small variation in overall mean values of live coral cover between MARAMP survey years does not necessarily reflect actual changes in overall coral cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Estimates of live coral cover from REA surveys generally exceeded levels recorded in towed-diver surveys; REA surveys target hard-bottom communities, whereas towed-diver surveys include a wider array of substrate types. Site-specific estimates of coral cover ranged from 8.8% to 66.7% with an overall mean of 34.1% (SE 5.7) for the 9 REA sites surveyed in 2007 (Maug was not surveyed for coral cover using the line-point-intercept method in 2003 or 2005).

The quadrat method was used during the 3 MARAMP survey years to assess coral-colony density. Overall mean coral-colony density from REA benthic surveys of forereef habitats at Maug increased from 29.7 colonies m^{-2} (SE 5.9) in 2003 to 45.1 colonies m^{-2} (SE 4.2) in 2005 and 47.2 colonies m^{-2} (SE 3) in 2007 (Fig. 16.5.1h). The same temporal pattern exists when only the 7 sites that were surveyed in all 3 survey years are examined. For example, observed mean coral-colony density increased from 26.3 colonies m^{-2} (SE 4.8) in 2003 to 46.1 colonies m^{-2} (SE 4.7) in 2005 and 47.5 colonies m^{-2} (SE 3.9) in 2007. This observed increase in coral-colony density may result from differences in the placement of individual quadrats, increased recruitment, or fragmentation of existing colonies.

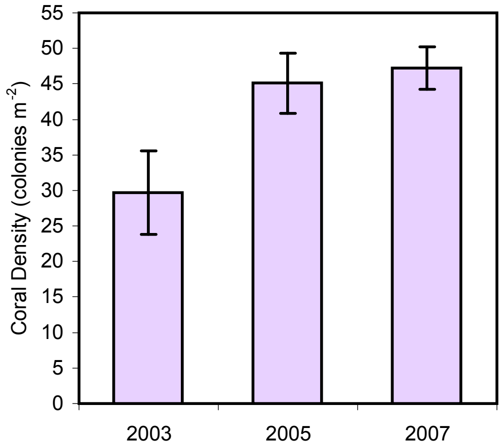


Figure 16.5.1h. Temporal comparison of mean coral-colony densities (colonies m^{-2}) from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to measure coral-colony density. Error bars indicate standard error (± 1 SE) of the mean.

Coral Generic Richness and Relative Abundance

Eight REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2003. At least 22 coral genera were observed at Maug. Generic richness ranged from 6 to 16 with a mean of 12.3 (SE 1.3) coral genera per site (Fig. 16.5.1i). The highest generic diversity was seen at both MAU-01 and MAU-03 in the west region and east caldera region, and the lowest generic diversity was recorded at MAU-04 in the east region.

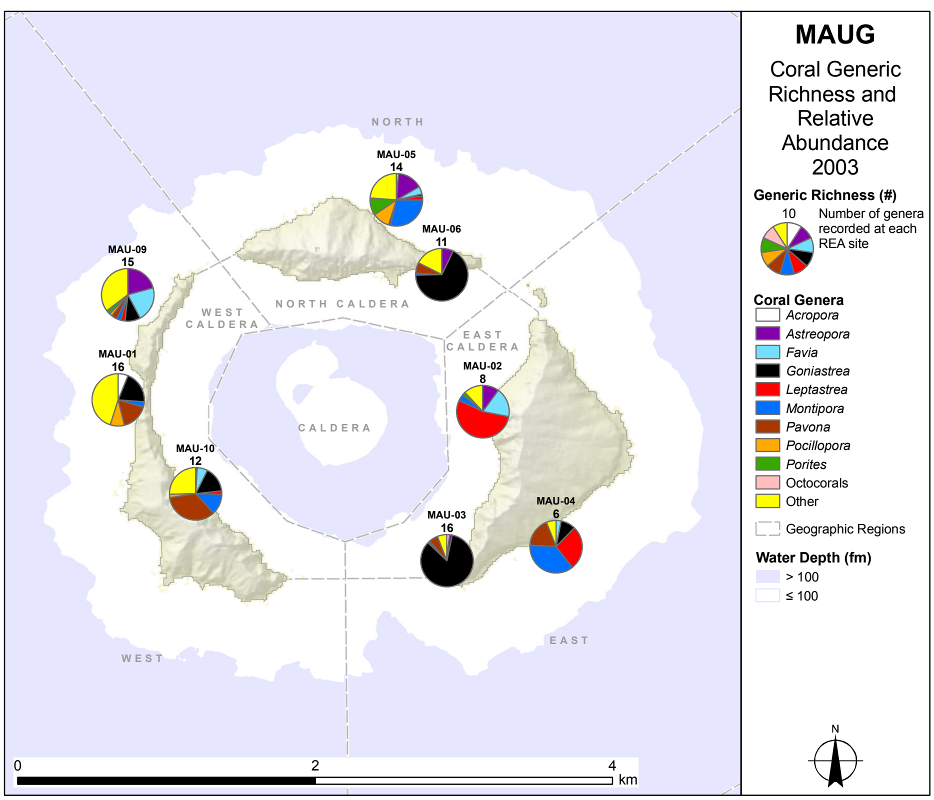


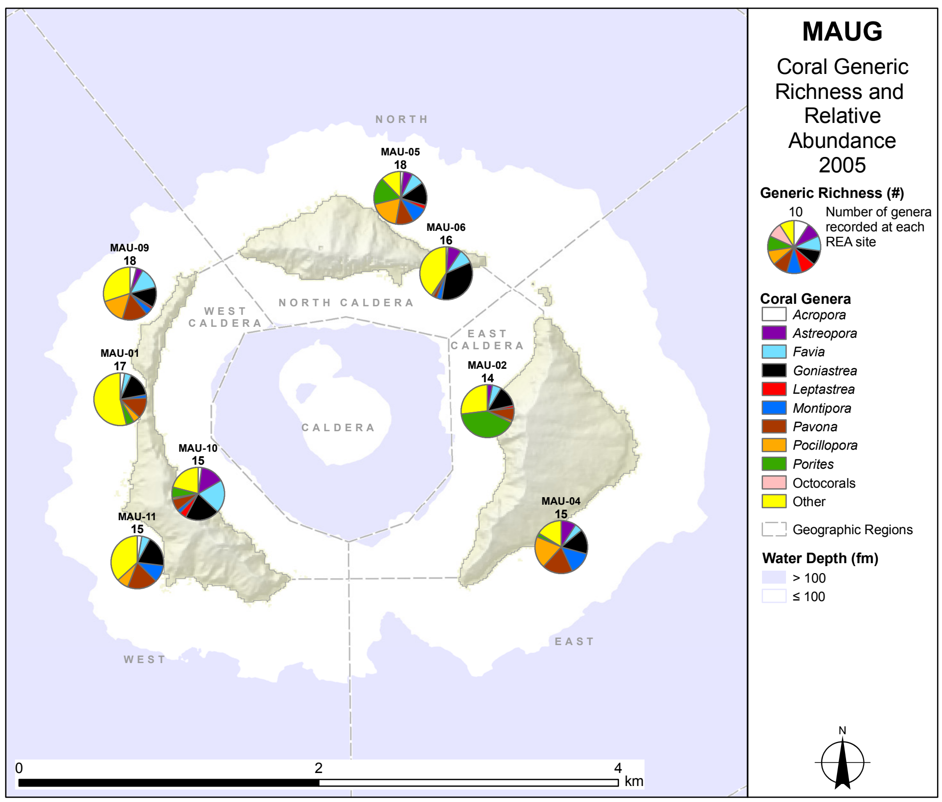
Figure 16.5.1i. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2003 to survey coral genera.

Goniastrea was the most numerically abundant genus, contributing 25.3% of the total number of colonies enumerated at Maug during MARAMP 2003. *Leptastrea*, *Montipora*, and *Pavona* were the next most numerically abundant genera, accounting for 11.2%, 11.3%, and 10.7 of the total number of colonies enumerated at Maug. All other genera individually contributed < 10% of the total number of colonies. *Goniastrea* dominated the coral fauna at MAU-03 and MAU-06 in the east caldera and north caldera regions, accounting for 81.2% and 66.5% of the total number of colonies at those sites (Fig. 165.1i). *Leptastrea* dominated the coral fauna at MAU-02 in the east caldera region, contributing 54% of the total number of colonies. *Pavona* was the most common genus at MAU-10, accounting for 34.7% of the total number of colonies. *Montipora* dominated MAU-04 and MAU-05 in the east and north regions, contributing 36.4% and 28.6% of the total number of colonies.

Eight REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2005. At least 26 coral genera were observed at Maug. Generic richness ranged from 14 to 18 with a mean of 16 (SE 0.5) coral genera per site (Fig. 16.5.1j). The highest generic diversity was seen at both MAU-09 and MAU-05 in the west and north regions, and the lowest generic diversity was recorded at MAU-02 in the east caldera region.

Goniastrea, *Porites*, and *Pavona* were the most numerically abundant genera, contributing 18%, 9%, and 11.6% of the total number of colonies enumerated at Maug during MARAMP 2005. All other genera individually contributed < 10% of the total number of colonies. *Porites* dominated at MAU-02 in the east caldera region, accounting for 40.5% of the total number of colonies (Fig. 16.5.1j). *Goniastrea* dominated at MAU-06 in the north caldera region, MAU-10 in the west caldera region, and MAU-11 in the west region, contributing 34.4%, 20.9%, and 19.1% of the total number of colonies.

Figure 16.5.1j. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2005 to survey coral genera.



Nine REA benthic surveys of forereef habitats were conducted using the quadrat method at Maug during MARAMP 2007. At least 27 coral genera were observed at Maug. Generic richness ranged from 11 to 20 with a mean of 15.4 (SE 1.0) genera per site (Fig. 16.5.1k). The highest generic diversity was seen at MAU-09 in the west region, and the lowest generic diversity was recorded at MAU-02 in the east caldera region.

Pocillopora, *Goniastrea*, *Pavona*, and *Porites* were the most numerically abundant genera, contributing 16%, 16.5%, 11.9%, and 7.8% of the total number of colonies enumerated at Maug during MARAMP 2007. All other genera individually accounted for < 10% of the total number of colonies. As seen in 2005 surveys, *Goniastrea* dominated at MAU-06 in the north caldera region and MAU-11 in the west region, contributing 42.8% and 20.1% of the total number of colonies, and *Porites* dominated the coral fauna at MAU-02 in the east caldera region, contributing 42.2% of the total number of colonies (Fig. 16.5.1k).

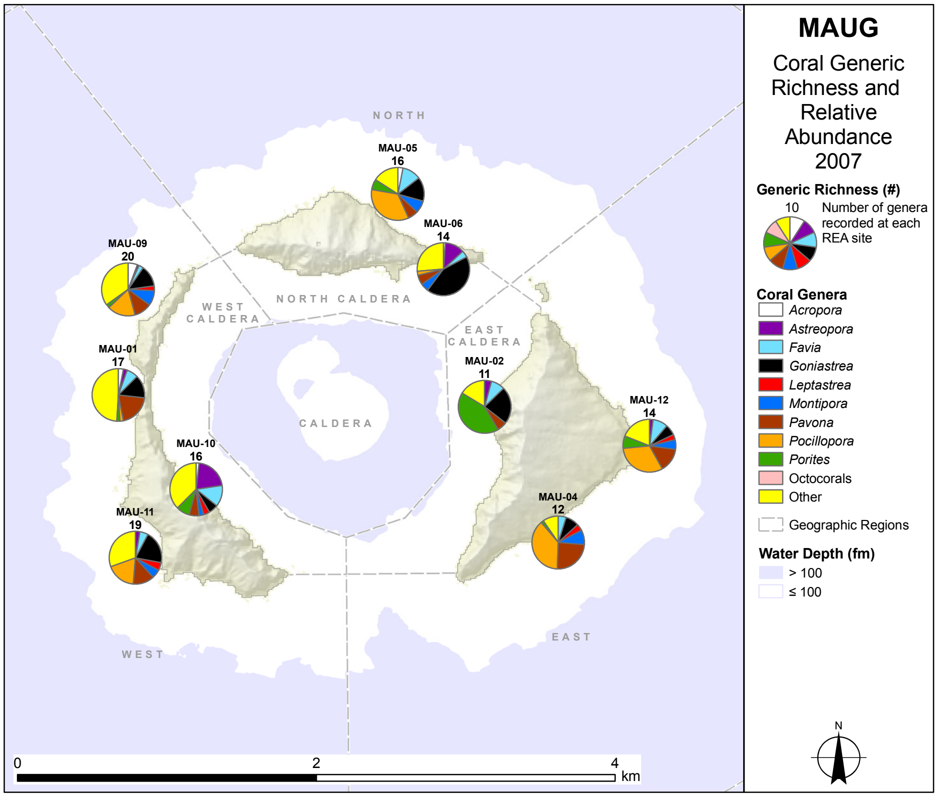


Figure 16.5.1k. Observations of coral generic richness and relative abundance of coral genera from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. The pie charts indicate percentages of relative abundance of key coral genera. The quadrat method was used in 2007 to survey coral genera.

The overall sample mean of generic richness on forereef habitats at Maug changed from 12.3 (SE 1.3) coral genera per site in 2003 to 16 (SE 0.5) and 15.4 (SE 1) coral genera per site in 2005 and 2007 (Fig. 16.5.1l). The same temporal pattern exists when only the 7 sites surveyed in all 3 MARAMP survey periods are examined. For example, mean generic richness increased from 11.7 (SE 1.2) coral genera per site in 2003 to 16.1 (SE 0.5) and 15.1 (SE 0.9) coral genera per site in 2005 and 2007.

During the 3 survey years, 29 coral genera were observed on forereef habitats at Maug. *Goniastrea* and *Pavona* were important components of the coral fauna, accounting for > 10% of the total number of colonies enumerated at Maug in the 3 MARAMP survey years. *Leptastrea* and *Montipora* were important components of the coral fauna in 2003, but their contribution decreased to < 10% of the total number of colonies enumerated in 2005 and 2007. Conversely, *Porites* was not a major part of the coral fauna overall in 2003 but in both 2005 and 2007 accounted for > 10% of the total number of colonies enumerated. Similarly, *Pocillopora* was not a major contributor to the coral fauna at Maug in 2003 or 2005, but its contribution exceeded 10% in 2007. All other taxa contributed < 10% of the total number of colonies enumerated in the 3 survey years.

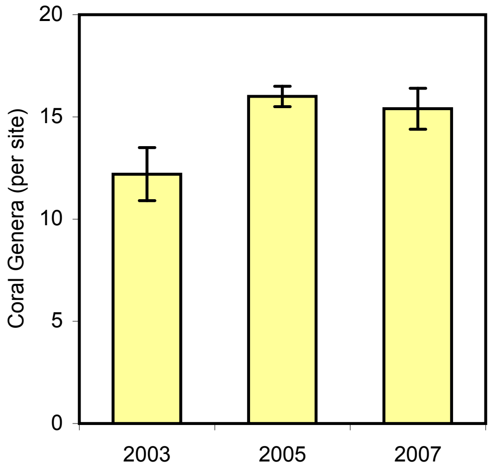
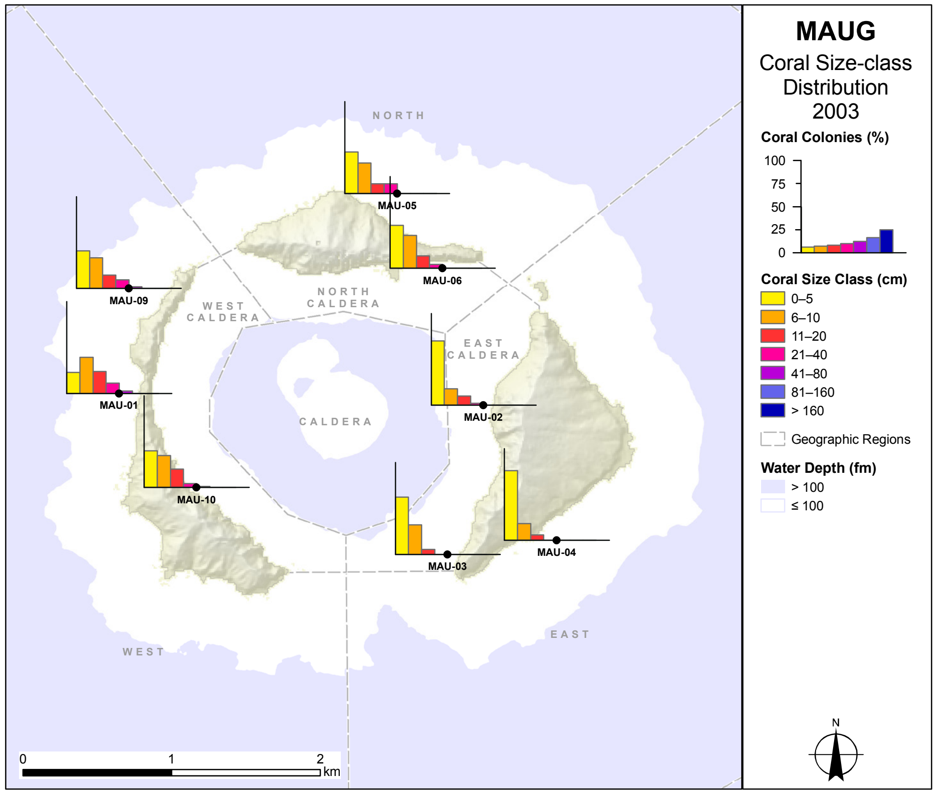


Figure 16.5.1l. Temporal comparison of overall mean numbers of coral genera per site from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to survey coral genera. Error bars indicate standard error (± 1 SE) of the mean.

Coral Size-class Distribution

During MARAMP 2003, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys shows that the majority (50.5%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1m). The next 4 size classes (6–10, 11–20, 21–40, and 41–80 cm) accounted for 31%, 13%, 5.2%, and 0.67% of colonies recorded. A majority (> 62%) of colonies at MAU-02, MAU-03, and MAU-04 in the east caldera and east regions were in the smallest size class (0–5 cm), but distributions were less strongly skewed at the other sites surveyed at Maug.

Figure 16.5.1m. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2003 to size corals.



During MARAMP 2005, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys conducted shows that the majority (60%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1n). The next 4 size classes (6–10, 11–20, 21–40, and 41–80) accounted for 23.5%, 10.4%, 4.7%, and 1.1% of colonies recorded, and corals with maximum diameters > 80 cm contributed 0.19% of colonies observed. At all REA sites surveyed in 2005, a near majority (> 48%) of corals were in the smallest size class (0–5 cm).

During MARAMP 2007, 8 REA benthic surveys of forereef habitats were conducted at Maug using the quadrat method. The coral size-class distribution from these surveys shows that the majority (62.7%) of corals had maximum diameters ≤ 5 cm (Fig. 16.5.1o). The next 4 size classes (6–10, 11–20, 21–40, and 41–80) accounted for 24.7%, 7.5%, 3.9%, and 1.1% of colonies recorded, and corals with maximum diameters > 80 cm contributed 0.2% to colonies observed. At all REA sites surveyed in 2007, a majority (> 52%) of corals were in the smallest size class (0–5 cm).

The quadrat method was used to establish size-class distributions on forereef habitats at Maug during the 3 MARAMP survey periods. Corals whose center fell within the borders of a quadrat (50 × 50 cm) were tallied and measured in 2 planar dimensions to the nearest centimeter. Fewer large colonies than small colonies can fall within a quadrat. This bias can contribute to higher counts of colonies in the smallest size classes and lower counts of colonies in the largest size classes compared to the actual relative colony densities. At each site, 15 or 16 such quadrats were examined (total survey area = 3.75 or 4 m^2), enabling observers to closely inspect and record each coral colony within the quadrat. For more on these survey methods, see Chapter 2, “Methods and Operational Background, Section 2.4.5: “Corals and Coral Disease.”

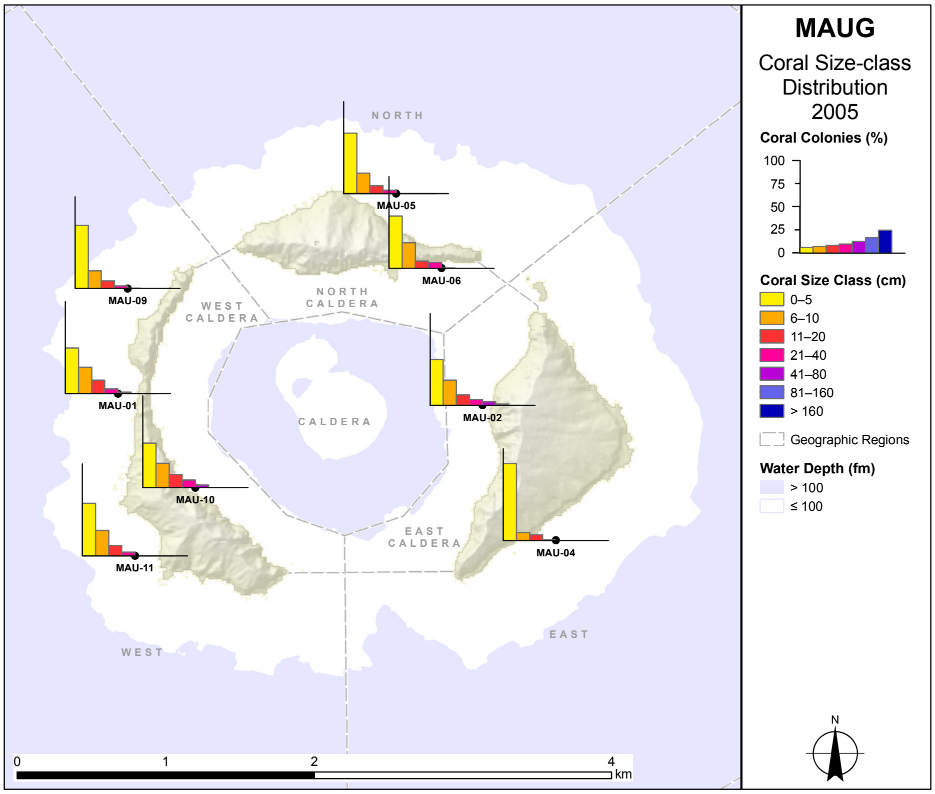


Figure 16.5.1n. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2005 to size corals.

During the 3 MARAMP survey years, corals in the smallest (0–5 cm) size class had the highest colony density recorded (Fig. 16.5.1p). The overall observed mean proportion of colonies at Maug that had a maximum diameter ≤ 5 cm increased from 50.5% in 2003 to 60% in 2005 and 62.7% in 2007. The increase between 2003 and 2005 may have resulted from recruitment, fragmentation of existing colonies, or both. Minor changes in overall and site-specific size-class distributions between 2005 and 2007 likely resulted from chance variation in the placement of individual quadrats.

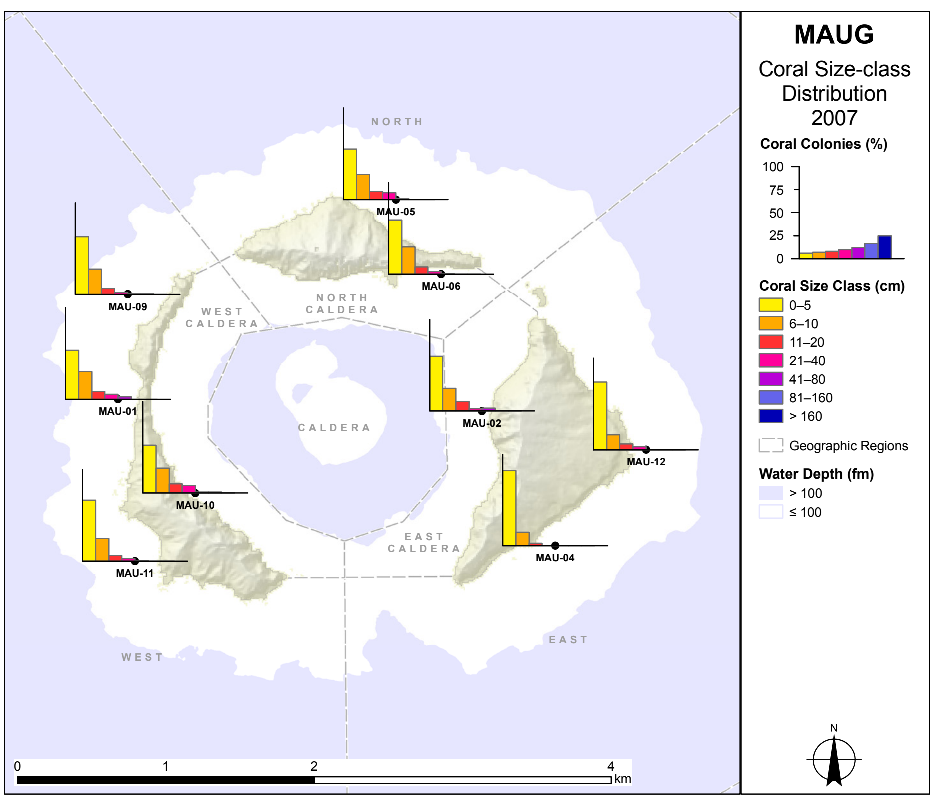
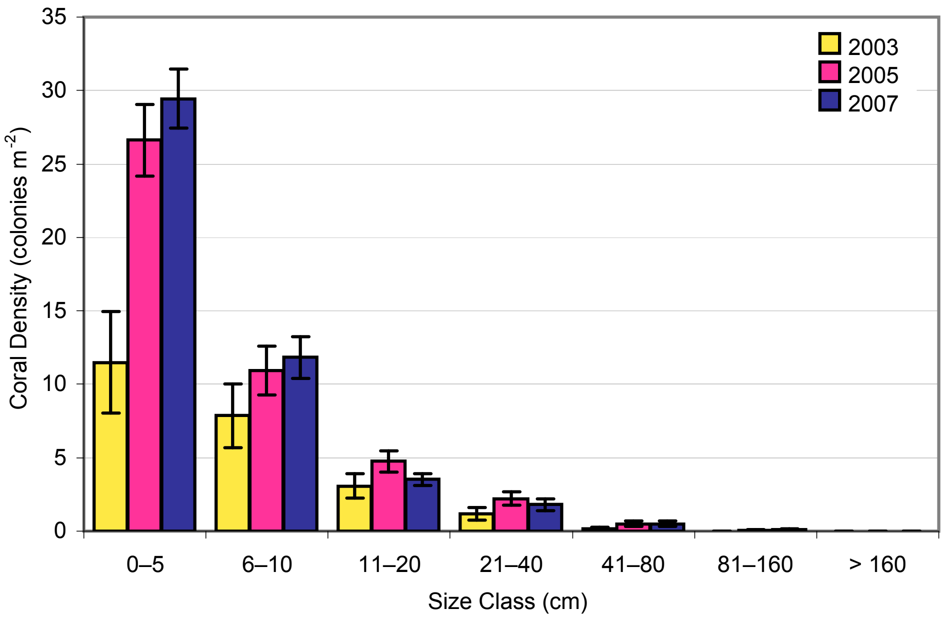


Figure 16.5.1o. Size-class distributions of hard corals from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. The observed size classes are color coded in a size-frequency chart at each REA site. The quadrat method was used in 2007 to size corals.

Figure 16.5.1p. Mean coral-colony densities (colonies m^{-2}) by size class from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2003, 2005, and 2007. The quadrat method was used in all 3 years to size corals. Error bars indicate standard error (± 1 SE) of the mean.



16.5.2 Surveys for Coral Disease and Predation

During MARAMP 2007, REA benthic surveys for coral disease and predation were conducted using the quadrat method at 9 sites on forereef habitats at Maug, covering a total area of 2700 m^2. Surveys detected 17 cases of disease, translating to an overall mean prevalence of 0.02% (SE 0.01), excluding predation. The use of the quadrat method for coral-colony counts at all REA sites at Maug resulted in higher-than-expected coral-colony densities, and, therefore, lower-than-expected disease-prevalence values. Four major disease conditions were observed at Maug. In order of numerical abundance, these conditions were subacute tissue loss, skeletal growth anomalies, bleaching, and fungal infection. Of the 9 sites surveyed, 4 contained disease: MAU-02 in the east caldera region, MAU-05 in the north region, MAU-10 in the west caldera region, and MAU-11 in the west region (Figs. 16.5.2a and b; the values of overall disease prevalence shown in Figure 16.5.2a include predation). All 4 disease states and nearly 65% of cases were recorded at MAU-05.

More than 60% of the afflictions recorded at Maug were observed on corals of the genus *Porites*. Other disease-hosting coral genera included *Acropora*, *Astreopora*, *Montipora*, *Goniastrea*, *Goniopora*, and *Platygyra*. Afflictions involving sub-acute tissue loss were present at MAU-05 in the north region on *Porites* and *Montipora* with overall prevalence of 0.04% and at MAU-02 in the east caldera region on *Goniopora* with prevalence of 0.01%. Cases of bleaching were detected on *Porites* at MAU-05 and MAU-11 in the north and west regions and on *Platygyra* at MAU-10 in the west caldera region. Disease conditions involving skeletal growth anomalies were observed at MAU-05, MAU-02, and MAU-10 on a diverse assortment of coral genera, including *Porites*, *Acropora*, and *Astreopora*.

Cases of coral predation attributable to crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails, such as snails from the genus *Drupella*, were the highest at MAU-10 and MAU-06 in the west caldera and north caldera regions with prevalence values of nearly 0.10% and 0.07%. These relatively high levels of coral predation appeared to correspond with survey areas where observed stressed-coral cover exceeded 10% during towed-diver surveys in the west caldera region near MAU-10 and in the north caldera region adjacent to MAU-06 (Figs. 16.5.1e and 16.5.2a). For more information about crown-of-thorns seastars (COTS) observed at Maug, see Section 16.7: “Benthic Macroinvertebrates.”

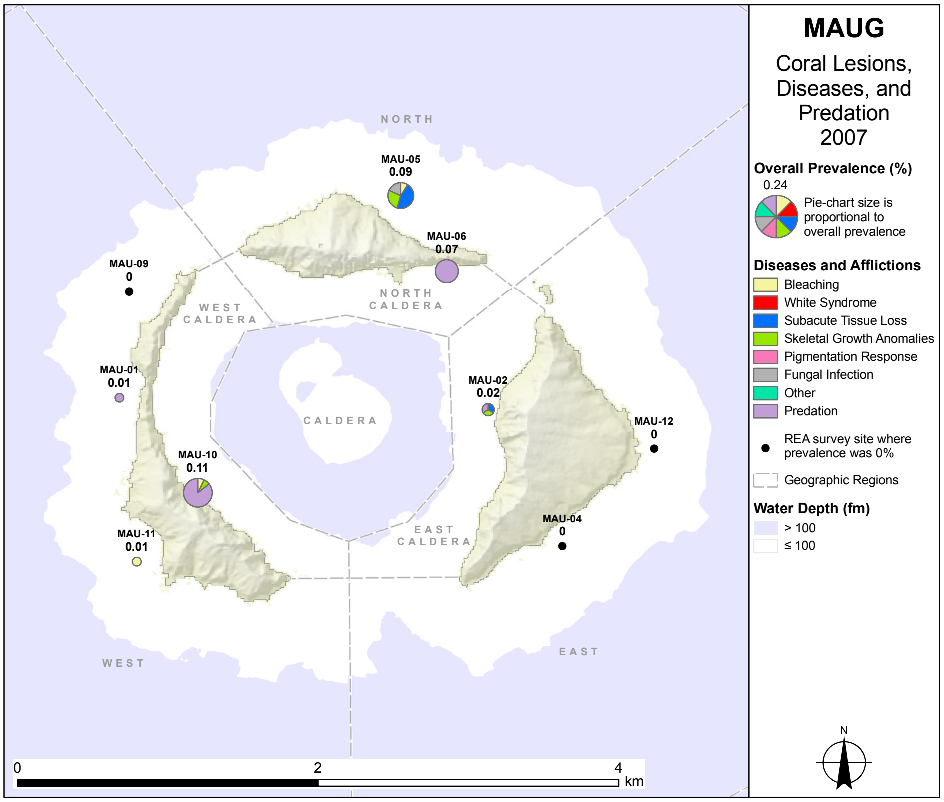


Figure 16.5.2a. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The color-coded portions of the pie charts indicate disease-specific prevalence.

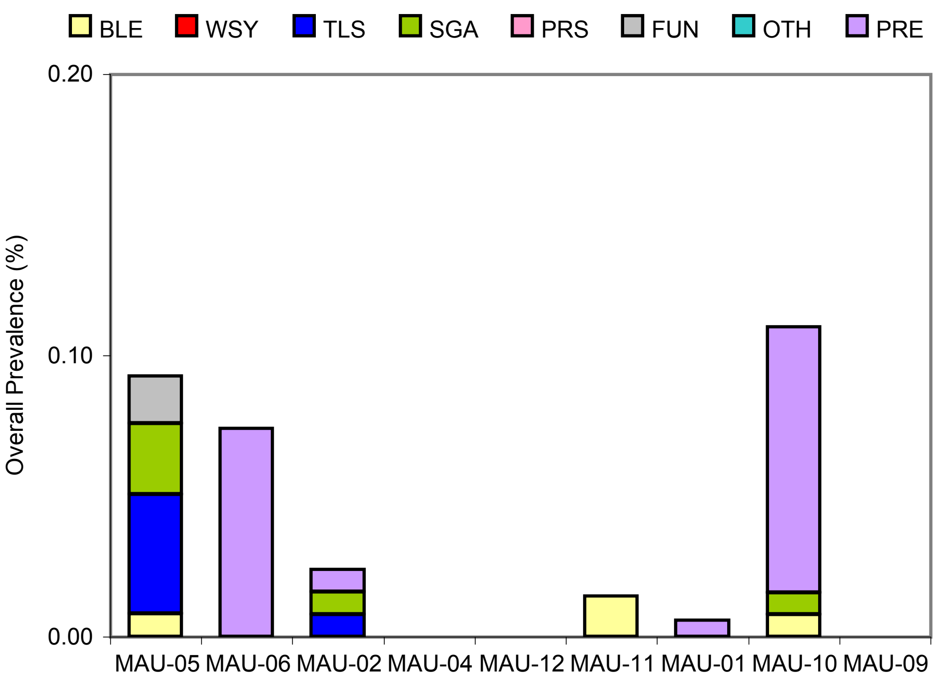


Figure 16.5.2b. Overall prevalence (%) observations of coral diseases and predation from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Prevalence was computed based on the estimated total number of coral colonies within the area surveyed for disease at each REA site. The order of conditions presented in the bars is the same as the order in the legend. BLE: bleaching; WSY: white syndrome; TLS: subacute tissue loss; SGA: skeletal growth anomalies; PRS: pigmentation response; FUN: fungal infection; OTH: algal and cyanophyte infections and other lesions of unknown etiology; PRE: predation by COTS or corallivorous snails.

16.6 Algae and Algal Disease

16.6.1 Algal Surveys

Algal Cover: Macroalgae and Turf Algae

From MARAMP 2003 towed-diver surveys, mean macroalgal cover on forereef habitats around the islands of Maug was 46% (SE 1.3). Observations of macroalgal cover in 2003 included both macroalgae and turf algae. The survey with the highest mean macroalgal cover of 65%, within a range of 40.1%–75%, occurred on the shallow forereef in the west region off the northwestern coast of West Island (Fig. 16.6.1a, top left panel; for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). The habitat in this area consisted of continuous reef with areas of rock boulders and bedrock of medium-high complexity. Medium-low complexity and the second-greatest mean macroalgal cover of 59% was recorded for the igneous bedrock and rock boulder habitat in the east region off the southeastern coast of East Island. A survey off the southwestern coast of West Island also reported high macroalgal cover with a mean of 56% over spur-and-groove pavement. In general, values of mean macroalgal cover were slightly higher on exposed reefs on the outer flanks than on the sheltered reefs within the caldera. The greatest exception to this pattern occurred on the reefs in the north caldera region where macroalgal cover of 54% was recorded for rock boulder and bedrock habitat.

TOAD surveys completed at Maug during MARAMP 2003 were conducted at depths of 20–225 m. Analyses of TOAD video footage obtained from 5 surveys suggests that there were little or no macroalgae, at least as seen in images; however, a sixth survey conducted at depths of 60–120 m off the southwestern coast of West Island, did record infrequent patches of macroalgal cover of up to 100%.

From MARAMP 2005 towed-diver surveys, mean cover of macroalgae on forereef habitats around Maug was 27% (SE 1.8). The survey with the highest mean macroalgal cover of 52%, within a range of 30.1%–75%, occurred off the southwestern coast of West Island over habitat of medium complexity (Fig. 16.6.1a, middle left panel). Around Maug, macroalgal cover generally was greater outside the caldera than within it. This difference was exemplified in the north region, off the northeastern coast of East Island, and off the northwestern coast of West Island, where greater-than-average values (49.5%, 36%, and 29.4%) of macroalgal cover were recorded. In the caldera, macroalgal-cover values were greatest for the survey conducted in the east caldera region with a mean of 26%. Each of the 3 other surveys conducted in the caldera reported low values of macroalgal cover that never exceeded 9.8%.

From MARAMP 2007 towed-diver surveys, mean cover of macroalgae on forereef habitats around Maug was 8% (SE 0.7). Two surveys reported the highest mean macroalgal cover of 10%, within a range of 1.1%–30%: 1 around the western end of North Island and 1 off the southwestern coast of West Island (Fig 16.6.1a, bottom left panel). The habitats observed during these surveys had predominantly light spur-and-groove continuous reef of medium to medium-high complexity and were dominated by species of the calcified green algal genus *Halimeda*. Off the northeastern coast of East Island, mean macroalgal cover of 8.3% was recorded and species of *Halimeda* and the red algal genus *Liagora* were frequently observed. All remaining surveys reported less-than-average levels of macroalgal cover.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Maug were conducted using the line-point-intercept method. Site-specific estimates of macroalgal cover ranged from 0% to 24.5% with an overall mean of 5% (SE 2.7). The REA survey with the highest macroalgal cover occurred in the east region at MAU-04 (Fig. 16.6.1b). Macroalgal cover from all other surveys was ≤ 9.8%. No macroalgae were recorded at 3 sites: MAU-01 and MAU-09 in the west region and MAU-10 in the west caldera region.

Turf-algal cover from these REA benthic surveys ranged from 22.5% to 57.8% with an overall mean of 41% (SE 3.7). The highest turf-algal cover occurred in the east region at MAU-04. Relatively high turf-algal-cover values of 55.9%, 46.1%, and 40.2% were found in the east region at MAU-12, north caldera region at MAU-06, and west region at MAU-01. The lowest turf-algal cover was recorded in the east caldera region at MAU-02.

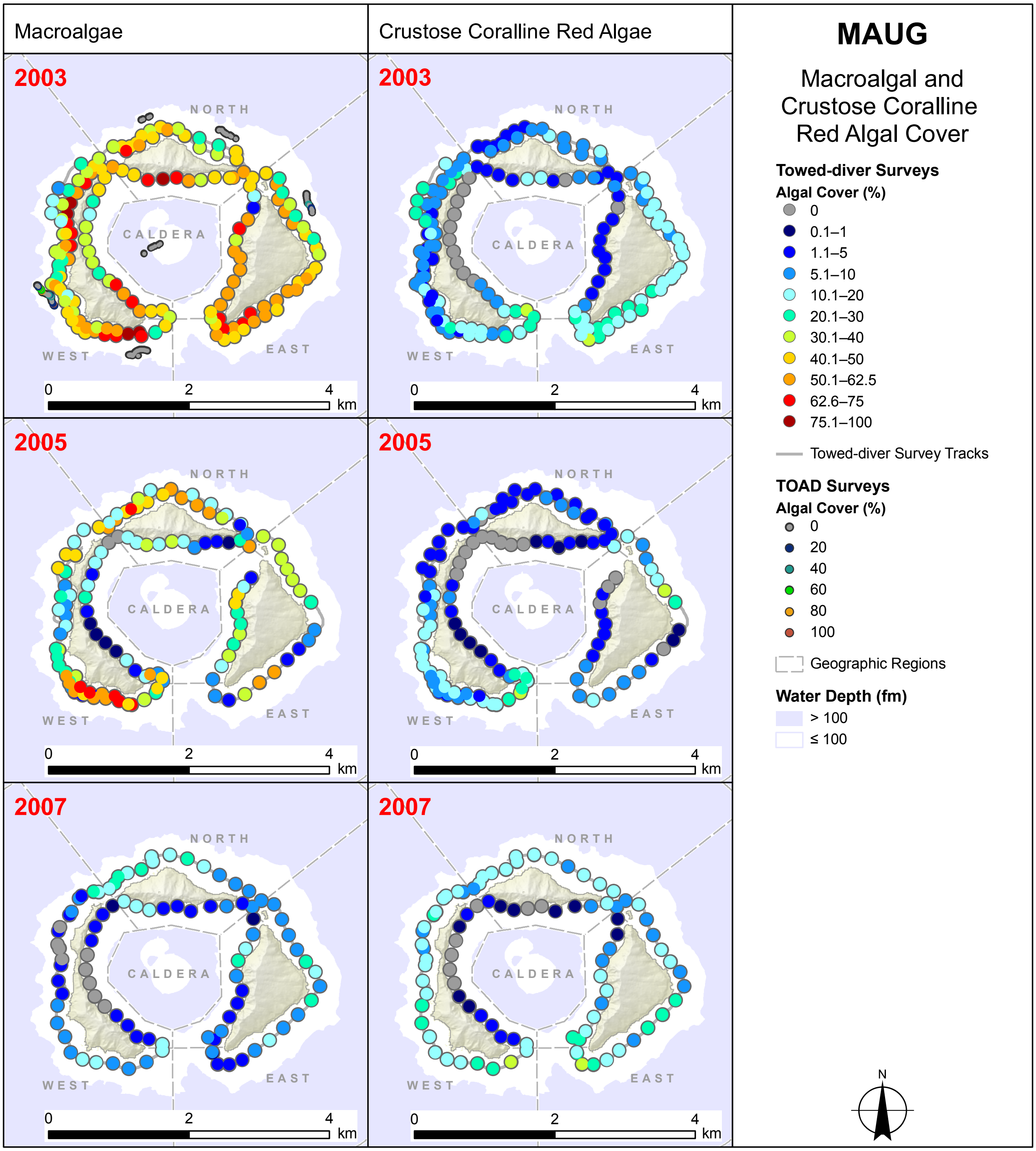


Figure 16.6.1a. Cover (%) observations for macroalgae and crustose coralline red algae from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007. Each large, colored point represents an estimate over a 5-min observation segment with a survey swath of ~ 200 × 10 m (~ 2000 m^2). The 2003 macroalgal panel shows observations of both macroalgae and turf algae (towed-diver surveys included turf algae only during MARAMP 2003). In this panel, each small, colored point represents an estimate of algal cover from TOAD surveys.

Algal Cover: Crustose Coralline Red Algae

From MARAMP 2003 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 10% (SE 0.6). The survey with the highest mean crustose-coralline-red-algal cover of 20%, within a range of 10.1%–40%, occurred along the southeastern coast of East Island (Fig. 16.6.1a, top right panel). A survey around the southern coast of West Island that wrapped into the west caldera region reported the second-greatest cover value for crustose coralline red algae with a mean of 18%. Other survey areas of relatively high cover with means of 15% included the northeastern coast of East Island and the northwestern coast of West Island.

From MARAMP 2005 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 8% (SE 0.8). The survey with the highest mean crustose-coralline-red-algal cover of 17%, within a range of 5.1%–75%, occurred around the southern end of West Island (Fig. 16.6.1a, middle right panel). The majority of this survey reported mean cover of ~ 12%; however, a single 5-min segment along a stretch of continuous reef reported cover of 62.6%–75%. The survey conducted along the northeastern coast of East Island also reported greater than average cover with a mean of 16%. Cover values for crustose coralline red algae were low in all caldera regions.

From MARAMP 2007 towed-diver surveys, mean cover of crustose coralline red algae on forereef habitats around Maug was 12% (SE 0.8) %. The survey with the highest mean crustose-coralline-red-algal cover of 22%, within a range of 5.1%–40%, occurred on the southeastern coast of East Island where continuous reef of medium-high complexity was the dominant structural feature (Fig. 16.6.1a, bottom right panel). A survey conducted along the southwestern coast of West Island also reported high cover values for crustose coralline red algae with a mean of 21%. Habitat complexity for spur-and-groove reef along the southwestern coast of West Island ranged from medium-high to very high. The forereef habitat along the northwestern coasts off both North and West Islands exhibited above-average cover of ~ 13.9%. All other towed-diver surveys conducted in 2007 reported below-average values for cover of crustose coralline red algae.

During MARAMP 2007, 9 REA benthic surveys of forereef habitats at Maug were conducted using the line-point-intercept method. Site-specific estimates of crustose-coralline-red-algal cover ranged from 0% to 10.8% with an overall mean of 4% (SE 1.2). The REA survey with the highest crustose-coralline-red-algal cover occurred in the west region at MAU-01 (Fig. 16.6.1b). No crustose coralline red algae were recorded at both MAU-06 in the north caldera region and MAU-10 in the west caldera region.

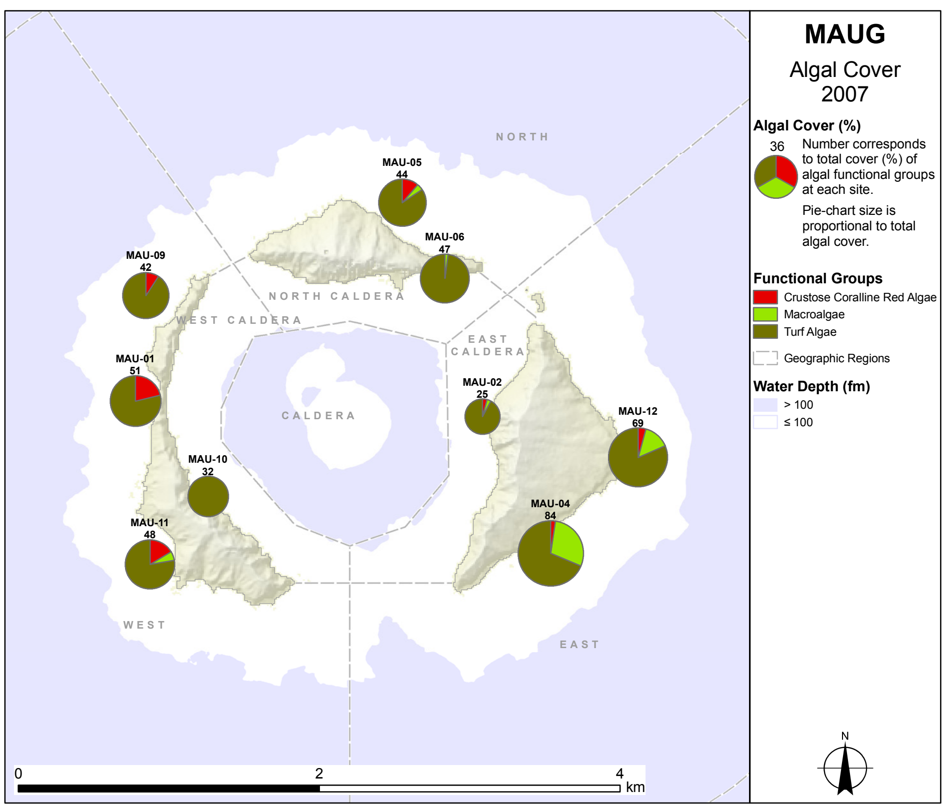


Figure 16.6.1b. Observations of algal cover (%) from REA benthic surveys of forereef habitats conducted using the line-point-intercept method at Maug during MARAMP 2007. The pie charts indicate algal cover by functional group, and values of total algal cover are provided above each symbol.

Algal Cover: Temporal Comparison

Between MARAMP 2005 and 2007, overall mean cover of macroalgal populations around Maug, based on towed-diver surveys of forereef habitats, varied by 19% (Fig. 16.6.1c). When considering survey results, keep in mind that turf algae were included, along with macroalgae, in towed-diver surveys of macroalgal cover only in 2003. Other factors, such as a change in season between survey periods, could have contributed to differences in algal cover (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Estimates of macroalgal cover collected around Maug show no recognizable patterns. In general, macroalgal populations were greater in surveys off the southwestern coast of West Island than in other areas surveyed around the islands of Maug. The southwestern reef experienced less change, when surveys in other areas reported substantial changes for the same time period.

Populations of crustose coralline red algae around Maug, based on towed-diver surveys on forereef habitats, varied as much as 5% in average cover of the benthos between MARAMP survey years. Estimates of cover values for crustose coralline red algae decreased 3% overall around Maug from 2003 to 2005. This observed decline was most apparent on the southeastern reefs off East Island with a decrease of 16% from 2003 to 2005. Conversely, crustose-coralline-red-algal cover around Maug increased 5% from 2005 to 2007. This increase was seen most on the southeastern reefs off East Island, where estimates made in 2003 and 2007 were similar. Across the 3 MARAMP survey years, populations of crustose coralline red algae were less abundant in the caldera than on the outer flanks of Maug.

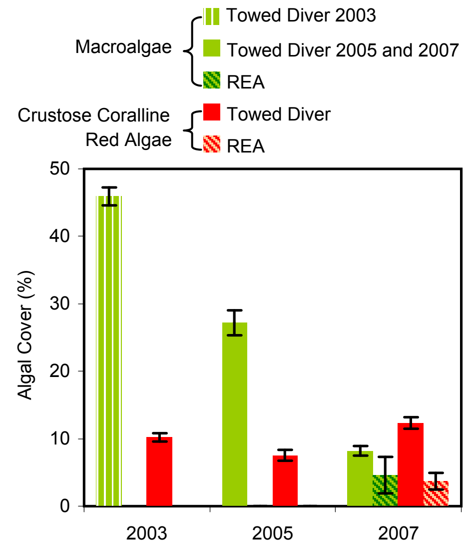


Figure 16.6.1c. Temporal comparison of algal-cover (%) values from surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Values of macroalgal cover from towed-diver surveys include turf algae only in 2003. No REA surveys using the line-point-intercept method were conducted at Maug in 2003 and 2005. Error bars indicate standard error (± 1 SE) of the mean.

Macroalgal Genera and Functional Groups

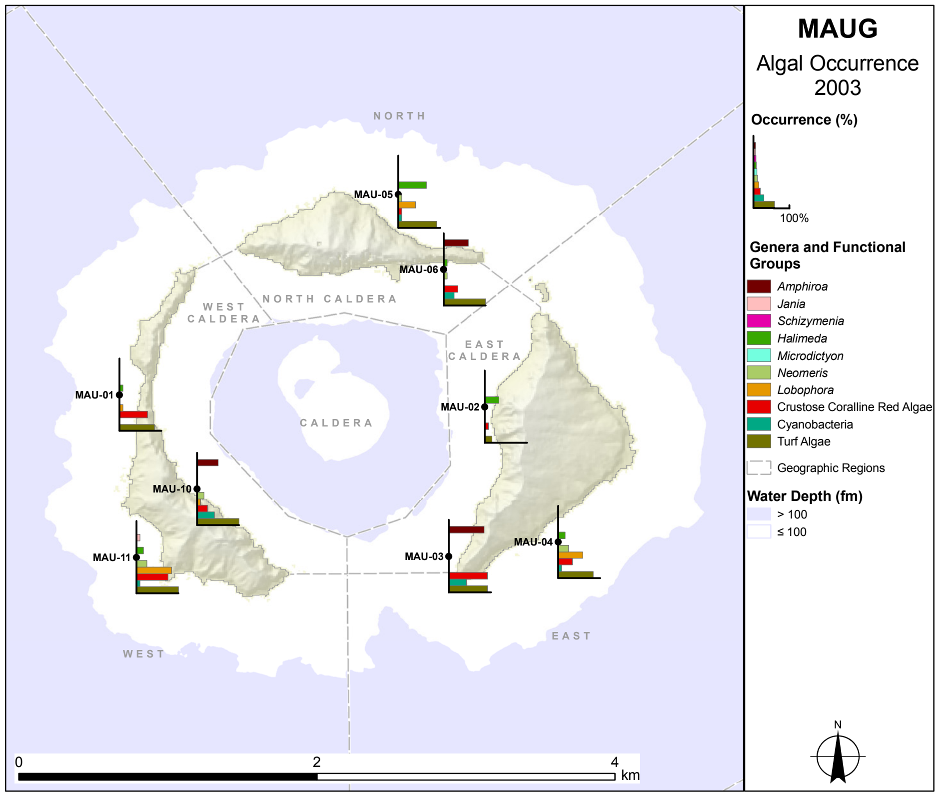
In the field, because of their small size or similarity in appearance, turf algae, crustose coralline red algae, cyanophytes (blue-green algae), and branched, nongeniculate coralline red algae were lumped into functional group categories. The generic names of macroalgae from field observations are tentative, since microscopic analysis is necessary for proper taxonomic identification. The lengthy process of laboratory-based taxonomic identification of all algal species collected at REA sites is about 90% complete for the northern islands of the Mariana Archipelago with hundreds of species identified so far. Ultimately, based on this microscopic analysis, the generic names of macroalgae reported in this section may change and algal diversity reported for each REA site likely will increase.

During MARAMP 2003, REA benthic surveys were conducted at 8 sites on forereef habitats at Maug. In the field, 19 macroalgal genera (5 red, 10 green, and 4 brown), containing at least 22 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. MAU-05 in the north region had the highest macroalgal generic diversity with 9 genera, containing 9 species, documented in the field. The lowest macroalgal generic diversity was found at MAU-03 in the east caldera region with 3 species representing 3 genera recorded.

Species of the red algal genus *Amphiroa* were common at Maug in 2003, occurring in 24% of sampled photoquadrats, although they only occurred in 83.3%, 58.3% and 50% of photoquadrats sampled at sites in the caldera, MAU-03, MAU-06, and MAU-10 (Fig. 16.6.1d). Species of *Halimeda* were also common around these islands, occurring in 18.8% of sampled photoquadrats overall and at 6 of the 8 sites surveyed. At MAU-05 in the north region, species of *Halimeda* occurred in 66.7% of sampled photoquadrats. Species of the green algal genera *Neomeris* and *Ventricaria* were common members of the algal community at Maug, occurring in 10.4% and 11.5% of photoquadrats sampled and at 5 and 6 of the sites surveyed. Species of the brown algal genus *Lobophora* occurred at 5 of the sites surveyed and in 25% of sampled photoquadrats. For the remaining 17 taxa tentatively identified in the field, no distinctive spatial patterns of distribution were observed at Maug.

Turf algae and crustose coralline red algae were both common in 2003, occurring in 83% and 43% of photoquadrats sampled at Maug. However, the occurrence of both functional groups varied widely with a range of 8.3%–91.7% for crustose coralline red algae and a range of 16.7%–100% for turf algae (Fig. 16.6.1d). Cyanobacteria were less common, occurring in 8.3%–41.7% of sampled photoquadrats at 6 of the 8 sites surveyed.

Figure 16.6.1d. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA algal surveys of forereef habitats conducted at Maug during MARAMP 2003. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.



During MARAMP 2005, REA benthic surveys were conducted at 8 sites on forereef habitats at Maug. In the field, 16 macroalgal genera (5 red, 8 green, and 3 brown), containing at least 17 species, as well as 4 additional algal functional groups—turf algae, crustose coralline red algae, nongeniculate calcified red algae, and cyanophytes—were observed. MAU-11, located in the west region southwest of West Island, had the highest macroalgal generic diversity with 9 genera, containing 10 species, documented in the field. The lowest macroalgal generic diversity was found at MAU-10 off the southeast coast of West Island with 4 species representing 4 genera recorded.

Species of the genera *Halimeda, Dictyosphaeria, Jania, Lobophora*, and *Ventricaria* were common at most sites surveyed at Maug in 2005, occurring in 32.4%, 11.1%, 12%, 38.9%, and 10.2% of sampled photoquadrats. Species of *Halimeda*, found at 7 of the 8 sites surveyed and 8.3%–100% of photoquadrats sampled at Maug, were the dominant macroalgae at most sites (Fig. 16.6.1e). Species of *Lobophora,* occurring at 6 of the 8 sites surveyed and in 8.3%–75% of sampled photoquadrats, were also a prominent part of the macroalgal community at Maug. Of the 16 macroalgal species tentatively identified in the field, only a select few showed any spatial pattern of distribution. Species of *Halimeda* were most prevalent at outer flank sites in the north and west regions of Maug, with the highest occurrence documented at MAU-05 off the northern coast of North Island. *Lobophora variegata* was commonly observed at forereef sites on the outer flanks at Maug, occurring in 50%–75% of sampled photoquadrats, but, in the caldera, was recorded only at a single site, occurring in 8.3% of photoquadrats sampled at MAU-02. Species of *Amphiroa* were found only at the caldera sites, MAU-02, MAU-06, and MAU-10, occurring in 25%–83.3% of photoquadrats sampled at these sites.

Turf algae and crustose coralline red algae were both common in 2005, occurring in 81% and 49% of photoquadrats sampled at Maug. Prevalent at all sites surveyed in 2005, turf-algal communities were recorded in 66.7%–100% of sampled photoquadrats (Fig. 16.6.1e). Communities of crustose coralline red algae were also found at all sites but with larger variability, occurring in 16.7%–100% of sampled photoquadrats. A minor component of the algal community at Maug were cyanobacteria, which were documented at 5 of the 8 sites surveyed and in 8.3%–25% of photoquadrats sampled at outer flank sites MAU-01 and MAU-05 and caldera sites MAU-02, MAU-06, and MAU-10. Nongeniculate, calcified, branched red algae were a minor component of the algal community at 2 sites, occurring in 25% and 8.3% of photoquadrats sampled at MAU-01 and MAU-09 in the west region.

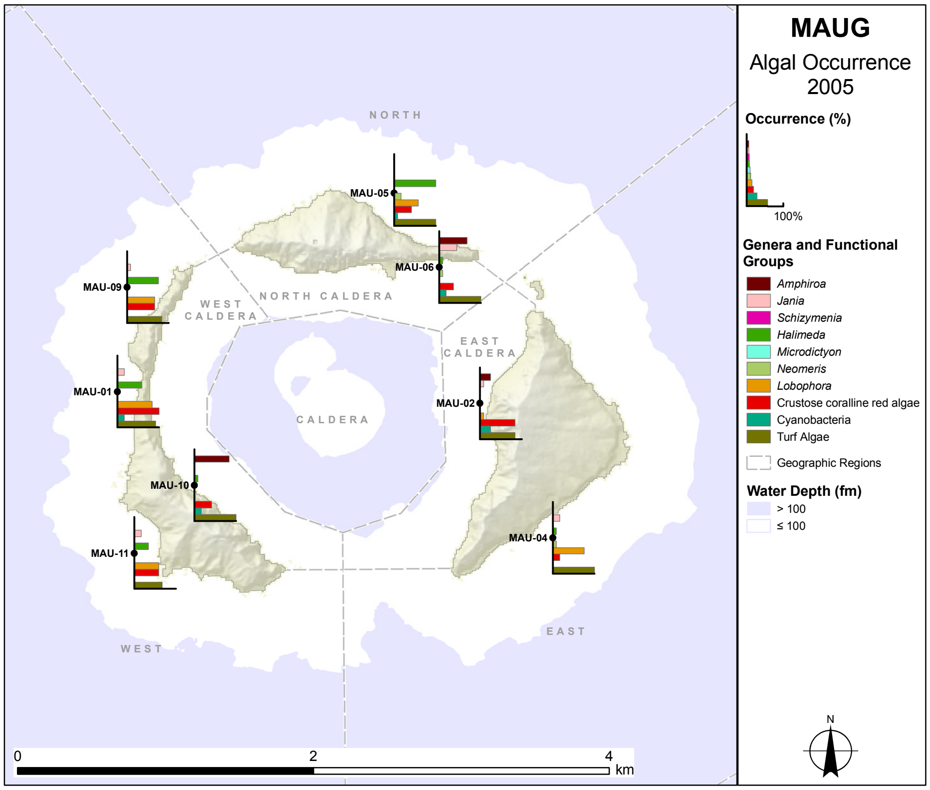


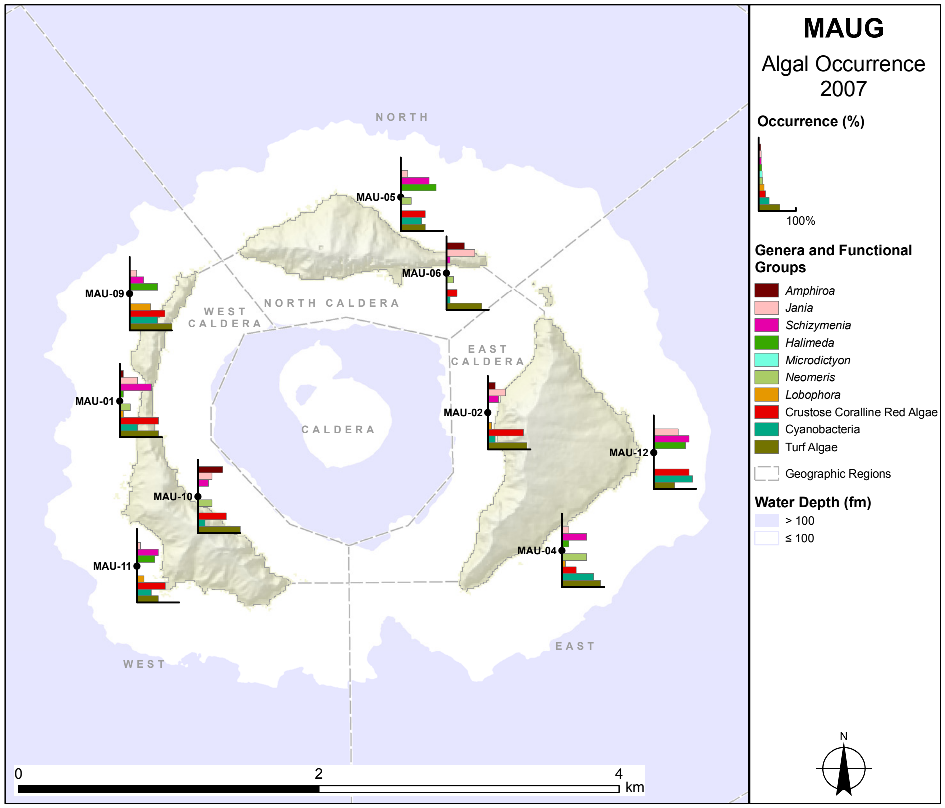
Figure 16.6.1e. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2005. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.

During MARAMP 2007, REA benthic surveys were conducted at 9 sites on forereef habitats at Maug. In the field, 21 macroalgal genera (7 red, 8 green, and 6 brown), containing at least 21 species, as well as 3 additional algal functional groups—turf algae, crustose coralline red algae, and cyanophytes—were observed. MAU-04, MAU-05, and MAU-10 in the east, north, and west caldera regions had the highest macroalgal generic diversity with 11 genera, containing 11 species, documented in the field at each site. The lowest macroalgal generic diversity was found at MAU-09 off the northwest coast of West Island with 6 species representing 6 genera recorded.

Species of the genera *Jania* and *Schizymenia* were common at every site surveyed at Maug in 2007, occurring in 33.3% and 47.2% of sampled photoquadrats. Species of the macroalgal genera *Halimeda, Dictyosphaeria, Neomeris, Lobophora, Peyssonnelia, Turbinaria*, and *Ventricaria* were found at most sites surveyed around these islands, occurring in 32.4%, 7.4%, 17.6%, 10.2%, 6.5%, 8.3%, and 6.5% of sampled photoquadrats (Fig. 16.6.1f). For all but a few of the 21 macroalgal species tentatively identified in the field, no distinctive spatial patterns of distribution were observed at Maug. Species of *Schizymenia* were generally more prevalent at the forereef sites on the outer flanks, occurring in 33.3%–83.3% of photoquadrates sampled at MAU-01, MAU-04, MAU-05, MAU-09, MAU-11, and MAU-12, than at sites in the caldera, occurring in 8.3%–25% of photoquadrats sampled at MAU-02, MAU-06, and MAU-10. Only found at the outer flank sites, species of *Halimeda* occurred in 8.3%–83.3% of phtotoquadrats sampled at MAU-01, MAU-04, MAU-05, MAU-09, MAU-11, and MAU-12. Species of *Amphiroa* were found in 16.7%–58.3% of photoquadrats sampled at caldera sites and in 8.3% of photoquadrats sampled at MAU-01, an outer flank site in the west region.

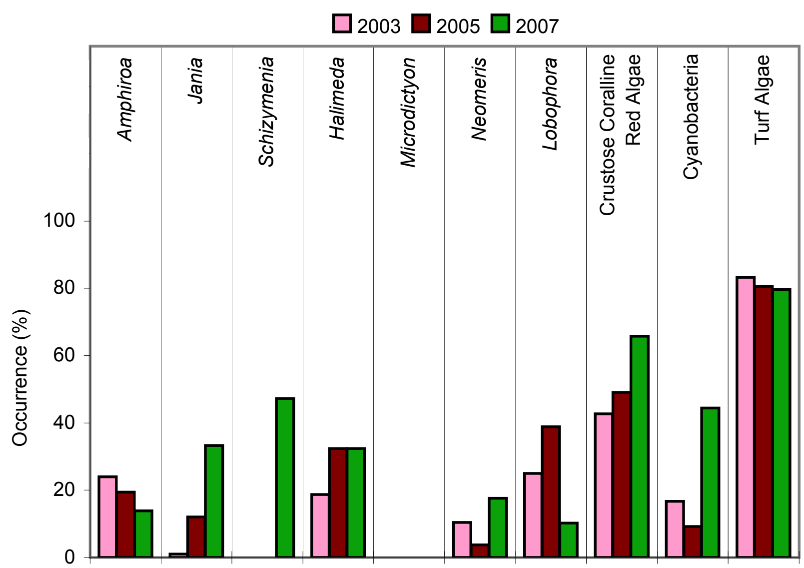
Turf algae, crustose coralline red algae, and cyanobacteria were all common in 2007, occurring in 80%, 66%, and 44% of photoquadrats sampled at Maug. Cyanobacteria were more prevalent at the outer flank sites with 33.3%–91.7% occurrence than at caldera sites with 8.3%–16.7% occurrence (Fig. 16.6.1f). No other spatial patterns of distribution were apparent for these functional groups.

Figure 16.6.1f. Observations of occurrence (%) for select macroalgal genera and algal functional groups from REA benthic surveys of forereef habitats conducted at Maug during MARAMP 2007. Occurrence is equivalent to the percentage of photoquadrats in which an algal genus or functional group was observed. The length of the x-axis denotes 100% occurrence.



The number of macroalgal genera recorded at Maug decreased from 19 to 16 genera between MARAMP 2003 and 2005 but increased to 21 genera during MARAMP 2007. Differences in survey effort and other factors likely can account for these small changes in estimated macroalgal diversity (for information on data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). Species of *Halimeda* were consistently the most prominent members of the macroalgal community across the 3 MARAMP survey years, with average occurrence of 18.8%–32.4% (Fig. 16.6.1g). A steady increase in abundance was observed for *Amphiroa*, also among the most prevalent genera with an aver-

Figure 16.6.1g. Temporal comparison of occurrence (%) values from REA benthic surveys of algal genera and functional groups conducted on forereef habitats at Maug during MARAMP 2003, 2005, and 2007.



age occurrence of 13.9%–24% in the MARAMP survey periods. Increases in occurrence were also recorded for species of *Jania* and *Turbinaria*, which were found in 1%–33.3% and 3.1%–8.3% of photoquadrats sampled over the 3 MARAMP survey years. Species of the green algal genera *Rhipidosiphon* and *Ventricaria* were found in 2.1% and 11.5% of sampled photoquadrats in 2003 but in only 0% and 6.5% of sampled photoquadrats in 2007. Species of the green algal genus *Caulerpa*, also prominent components of the algal community during the 3 MARAMP survey years, were found in 7.4%–10.2% of sampled photoquadrats, but no distinct patterns in abundance were observed for this genus.

Turf algae occurred in 79.6%–83.3% of photoquadrats sampled at Maug during MARAMP 2003, 2005, and 2007 with slight decreases in abundance (Fig. 16.6.1g). Crustose coralline red algae were found in 42.7%–65.7% of photoquadrats sampled in the 3 MARAMP survey years with an increase in abundance each year. No patterns in abundance were observed at Maug for cyanobacteria, which occurred in 9.3%–44.4% of sampled photoquadrats.

16.6.2 Surveys for Coralline-algal Disease

During MARAMP 2007, REA benthic surveys for coralline-algal disease were conducted in concert with coral-disease assessments at 9 sites on forereef habitats at Maug. These surveys covered a total reef area of 2700 m^2 and detected 12 cases. These numbers translate to a low overall mean density of 0.4 cases 100 m^{-2} (SE 0.3), compared to survey results for other areas in the Mariana Archipelago. Only 1 major type of coralline-algal disease was observed at Maug: coralline lethal orange disease, present at 3 of the 9 sites surveyed. The greatest density of 2.3 cases 100 m^{-2} was found at MAU-01 in the west region, and much lower disease densities were recorded at the other 2 sites (Fig. 16.6.2a).

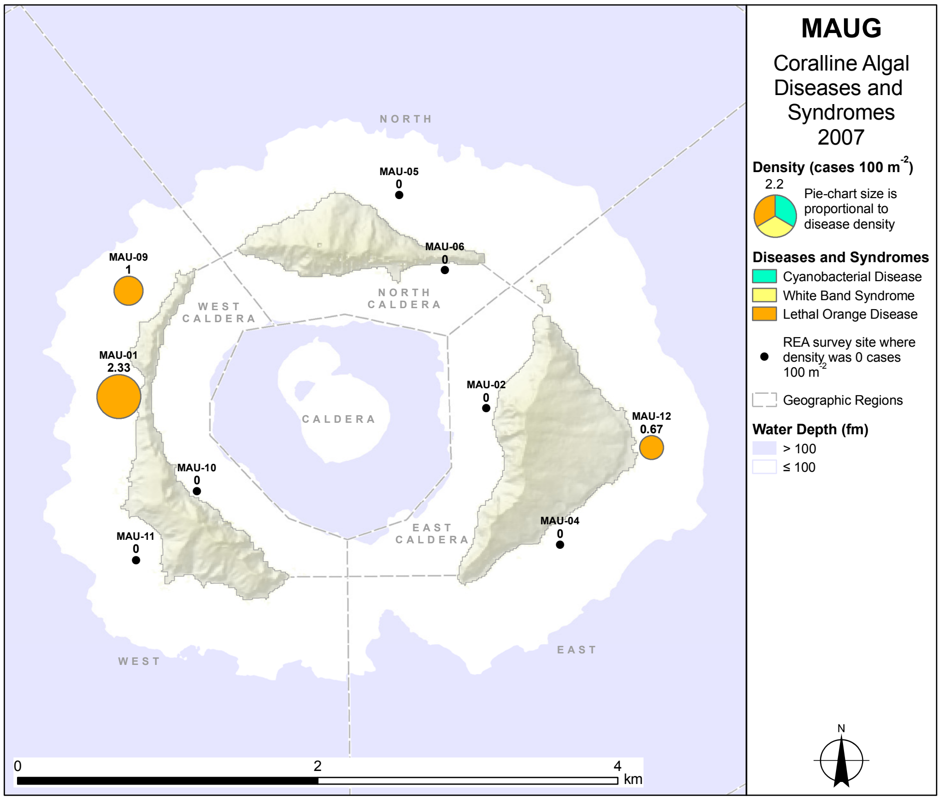


Figure 16.6.2a. Densities (cases 100 m^{-2}) of coralline-algal diseases from REA benthic surveys conducted on forereef habitats at Maug during MARAMP 2007. The color-coded portions of the pie charts indicate disease-specific density.

16.7 Benthic Macroinvertebrates

16.7.1 Benthic Macroinvertebrate Surveys

Four groups of benthic macroinvertebrates—sea urchins, sea cucumbers, giant clams, and crown-of-thorns seastars (COTS)—were monitored on forereef habitats around the islands of Maug through REA and towed-diver benthic surveys during MARAMP 2003, 2005, and 2007. This section describes by group the results of these surveys. A list of additional taxa observed during REA invertebrate surveys is provided in Chapter 3: "Archipelagic Comparisons."

Monitoring these 4 groups of ecologically and economically important taxa provides insight into the population distribution, community structure, and habitats of the coral reef ecosystems of the Mariana Archipelago. High densities of the corallivorous COTS can affect greatly the community structure of reef ecosystems. Giant clams are filter feeders that are sought after in the Indo-Pacific for their meat, which is considered a delicacy, and for their shells. Sea cucumbers, sand-producing detritus foragers, are harvested for food. Sea urchins are important algal grazers and bioeroders.

In 2003, 8 REA surveys and 16 towed-diver benthic surveys were conducted around Maug, and, in 2005, 8 REA surveys and 13 towed-diver benthic surveys were performed. Data are reported for 9 REA surveys and 10 towed-diver benthic surveys conducted in 2007. When considering survey results from towed-diver surveys, keep in mind that cryptic or small organisms can be difficult for divers to see, so the density values presented in this report, especially of giant clams and sea urchins, may under-represent the number of individuals present.

Minor fluctuations in observed densities between MARAMP survey periods occurred with all target groups. For each target organism, temporal patterns of overall mean macroinvertebrate density on forereef habitats around Maug–from towed-diver benthic surveys during MARAMP 2003, 2005, and 2007—are shown later in this section (Figs. 16.7.1d, h, l, and p).

Giant Clams

During MARAMP 2003, species of *Tridacna* giant clams were observed at 7 of the 8 REA sites surveyed and in 14 of the 16 towed-diver surveys conducted around Maug (Fig. 16.7.1a). The overall mean density of giant clams from REA surveys was 19.75 organisms 100 m^{-2} (SE 9.42), and the overall mean density from towed-diver surveys was 0.52 organisms 100 m^{-2} (SE 0.13). Survey results suggest that giant clams were most abundant at REA site MAU-06 in the north caldera region with 74 organisms 100 m^{-2}, followed by MAU-01 with 44 organisms 100 m^{-2}.

Among all towed-diver surveys conducted around Maug in 2003, the survey completed along the southern shore of North Island had the highest mean density of giant clams with 3.27 organisms 100 m^{-2}; segment densities from this survey ranged from 0.07 to 8.92 organisms 100 m^{-2} (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). The second-greatest mean density of giant clams from a towed-diver survey was 1.59 organisms 100 m^{-2}, recorded in the west caldera region; segment densities ranged from 0.05 to 4.09 organisms 100 m^{-2}. The third-greatest mean density of giant clams from a towed-diver survey was 1.43 organisms 100 m^{-2}, recorded in the west region; segment densities ranged from 0 to 10.99 organisms 100 m^{-2}.

During MARAMP 2005, giant clams were observed at 5 of the 8 REA sites surveyed and in 12 of the 13 towed-diver surveys conducted around Maug (Fig. 16.7.1b). The overall mean density of giant clams from REA surveys was 5.25 organisms 100 m^{-2} (SE 3.13), and the overall mean density from towed-diver surveys was 0.38 organisms 100 m^{-2} (SE 0.08). Survey results suggest giant clams were most prevalent at MAU-06 in the north caldera region with 26 organisms 100 m^{-2}, followed by MAU-10 off the eastern coast of West Island with 8 organisms 100 m^{-2}.

Among all towed-diver surveys conducted around Maug in 2005, the survey completed in the north caldera region had the highest mean density of giant clams with 1.33 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 4.92 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 1.01 organisms 100 m^{-2}, recorded on a survey that started in the west caldera region along the northeast-facing coast of West Island and ended in the north caldera region along the southwest-facing coast of North Island; segment densities ranged from 0 to 2.64 organisms 100 m^{-2}.

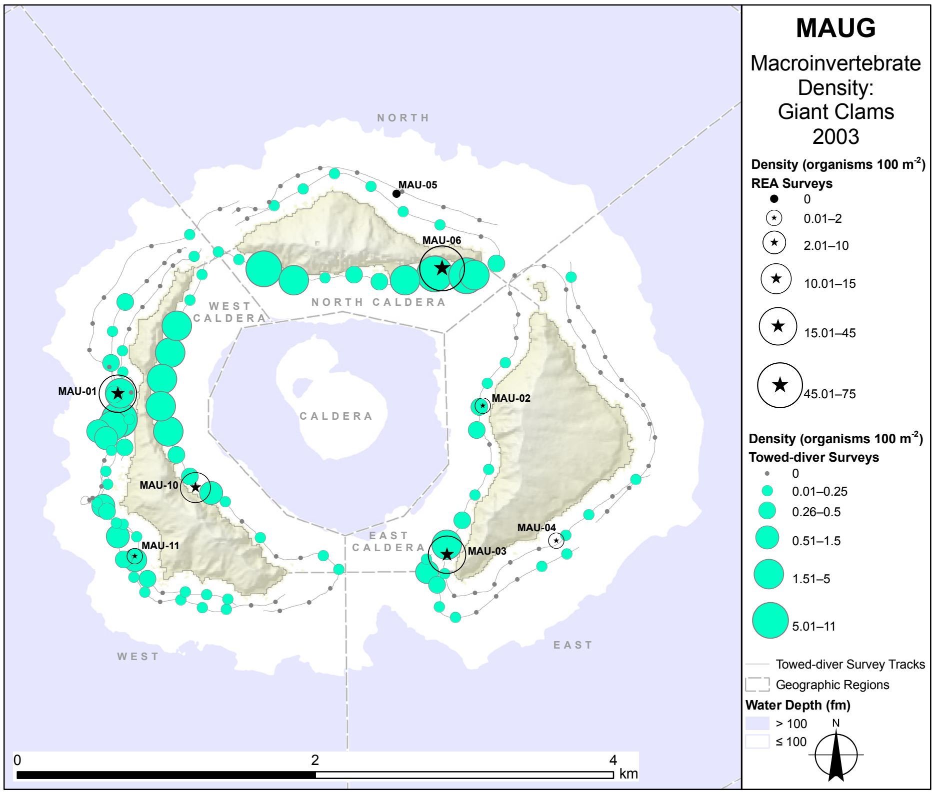


Figure 16.7.1a. Densities (organisms 100 m-²) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2007, giant clams were observed at all 9 REA sites surveyed and in 10 towed-diver surveys conducted around Maug (Fig. 16.7.1c). The overall mean density of giant clams from REA surveys was 5.41 organisms 100 m^{-2} (SE 2.3), and the overall mean density from towed-diver surveys was 0.27 organisms 100 m^{-2} (SE 0.05). Survey results suggest giant clams were most abundant at MAU-01 in the west region with 17.67 organisms 100 m^{-2}, followed by MAU-06 in the north caldera region with 17.33 organisms 100 m^{-2}.

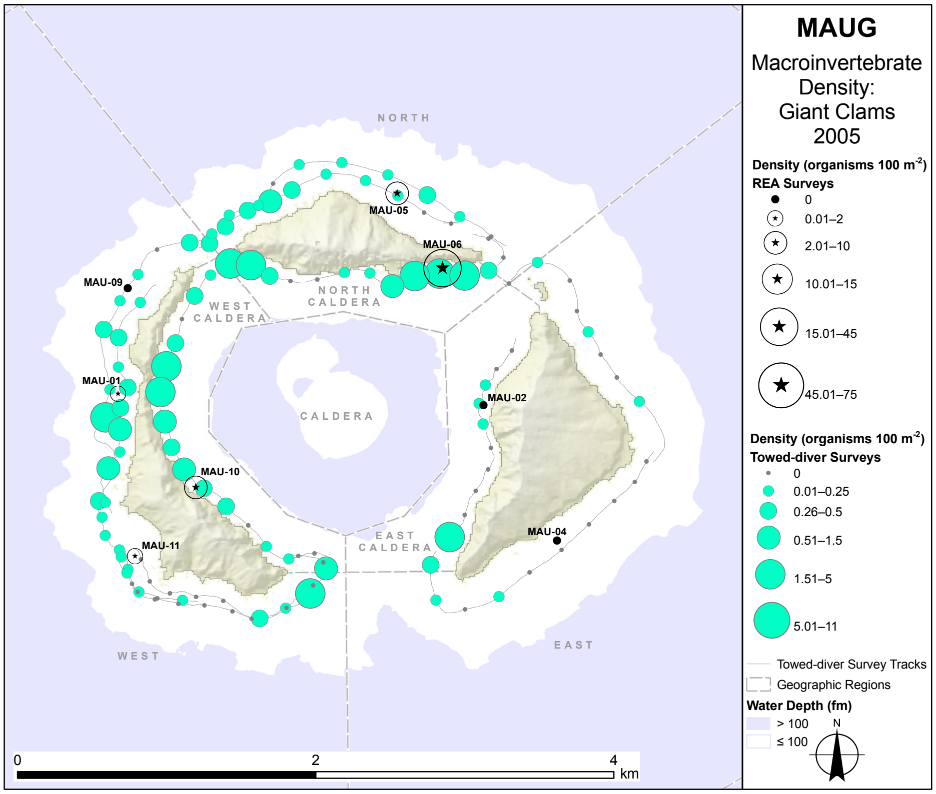
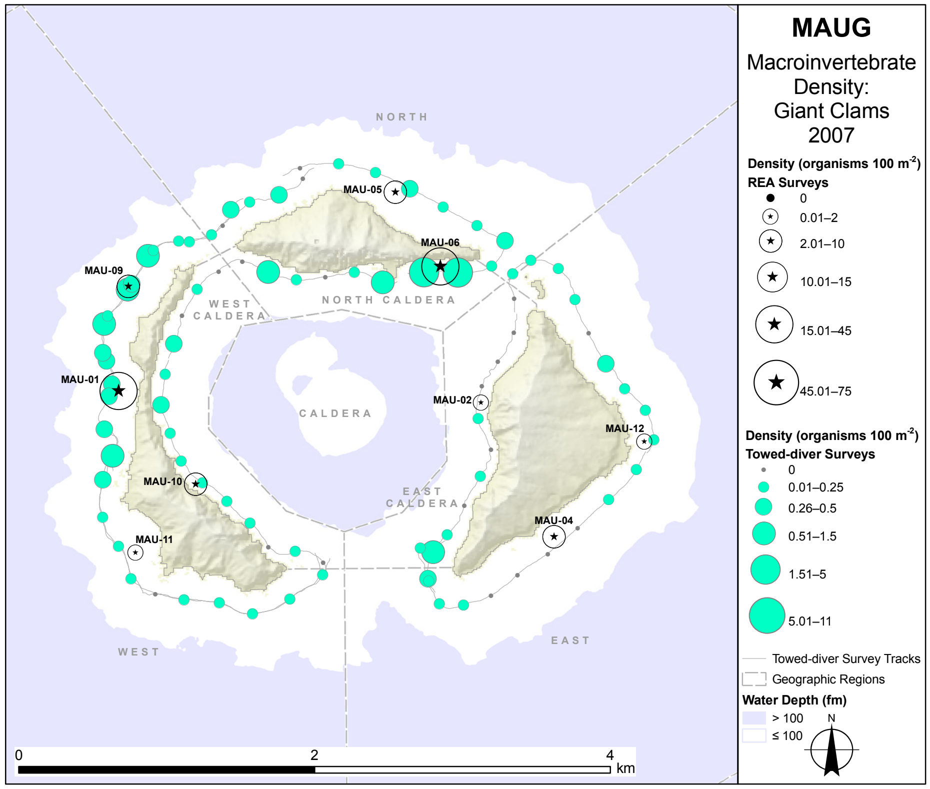


Figure 16.7.1b. Densities (organisms 100 m-²) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

Among all towed-diver surveys conducted around Maug in 2007, the survey completed along the southern coast of North Island in the north caldera region had the highest mean density of giant clams with 0.81 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 3.52 organisms 100 m^{-2}. The second-greatest mean density of giant clams from a towed-diver survey was 0.51 organisms 100 m^{-2}, recorded along the western shore of West Island; segment densities ranged from 0.05 and 1.33 organisms 100 m^{-2}.

Figure 16.7.1c. Densities (organisms 100 m^{-2}) of giant clams from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.



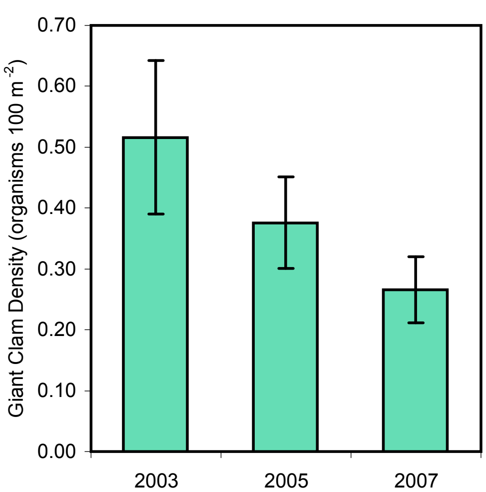


Figure 16.7.1d. Temporal comparison of mean densities (organisms m^{-2}) of giant clams from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested high abundance of giant clams around Maug during the 3 MARAMP survey periods, relative to the rest of the Mariana Archipelago. In the 3 survey years, the greatest densities of giant clams were recorded in the north caldera region along the southern coast of North Island. The overall observed mean density of giant clams at Maug was lower in 2007 than in 2003 (Fig. 16.7.1d). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of giant clams (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

Crown-of-thorns Seastars (COTS)

During MARAMP 2003, no crown-of-thorns seastars (*Acanthaster planci*) were observed at the 8 REA sites surveyed at Maug, but 5 of the 16 towed-diver surveys had recordings of COTS (Fig. 16.7.1e), with an overall mean density of 0.045 organisms 100 m^{-2} (SE 0.017). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density of COTS with 0.685 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.569 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.011 organisms 100 m^{-2}, recorded along the southern shore of East Island; segment densities ranged from 0 to 0.111 organisms 100 m^{-2}.

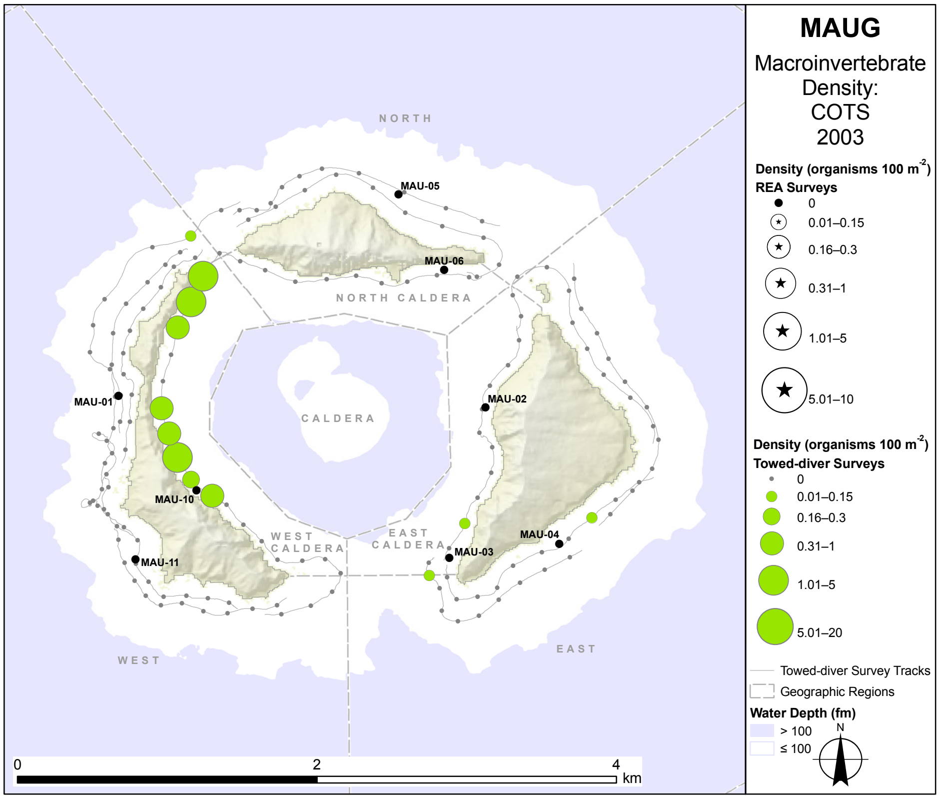


Figure 16.7.1e. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2005, no COTS were observed at the 8 REA sites surveyed at Maug, but 6 of the 13 towed-diver surveys had recordings of COTS (Fig. 16.7.1f), with an overall mean density of 0.015 organisms 100 m^{-2} (SE 0.005). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density with 0.097 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.41 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.048 organisms 100 m^{-2}, recorded in the north caldera region; segment densities ranged from 0 to 0.173 organisms 100 m^{-2}.

During MARAMP 2007, no COTS were observed at the 9 REA sites surveyed at Maug, but 5 of 10 towed-diver surveys had recordings of COTS (Fig. 16.7.1g), with an overall mean density of 0.013 organisms 100 m^{-2} (SE 0.004). Among all towed-diver surveys conducted around Maug, the survey completed in the west caldera region had the highest mean density with 0.048 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.294 organisms 100 m^{-2}. The second-greatest mean density of COTS from a towed-diver survey was 0.026 organisms 100 m^{-2}, recorded during a survey that stretched from the north caldera region along the southern coast of North Island to the west caldera region along the northeastern coast of West Island; segment densities ranged from 0 to 0.156 organisms 100 m^{-2}.

Figure 16.7.1f. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

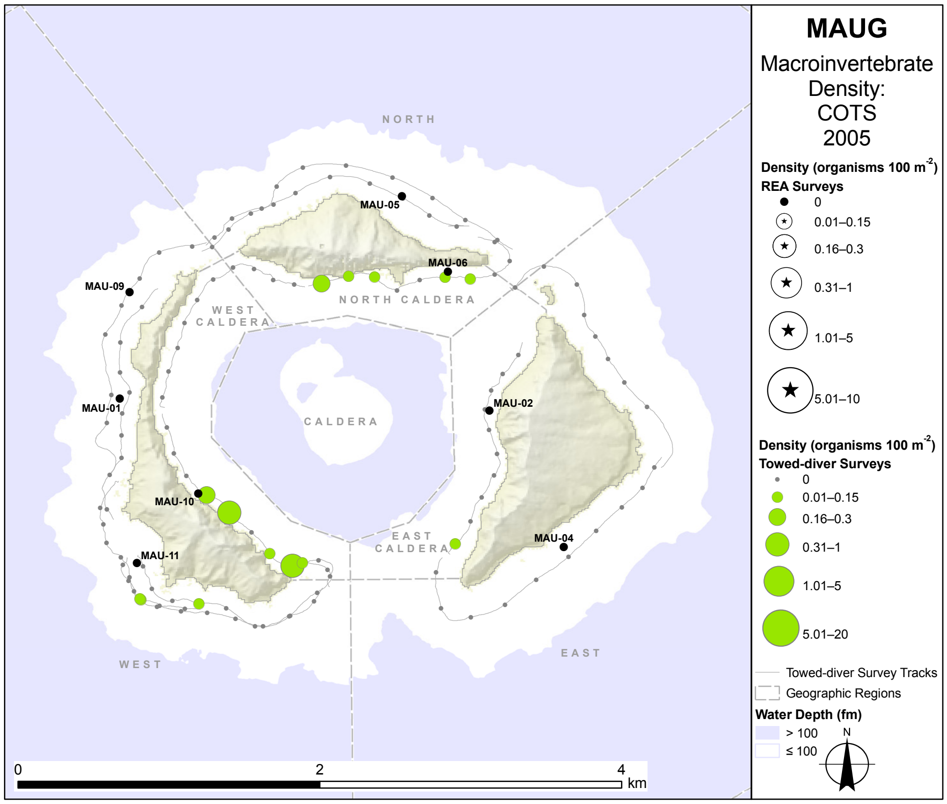
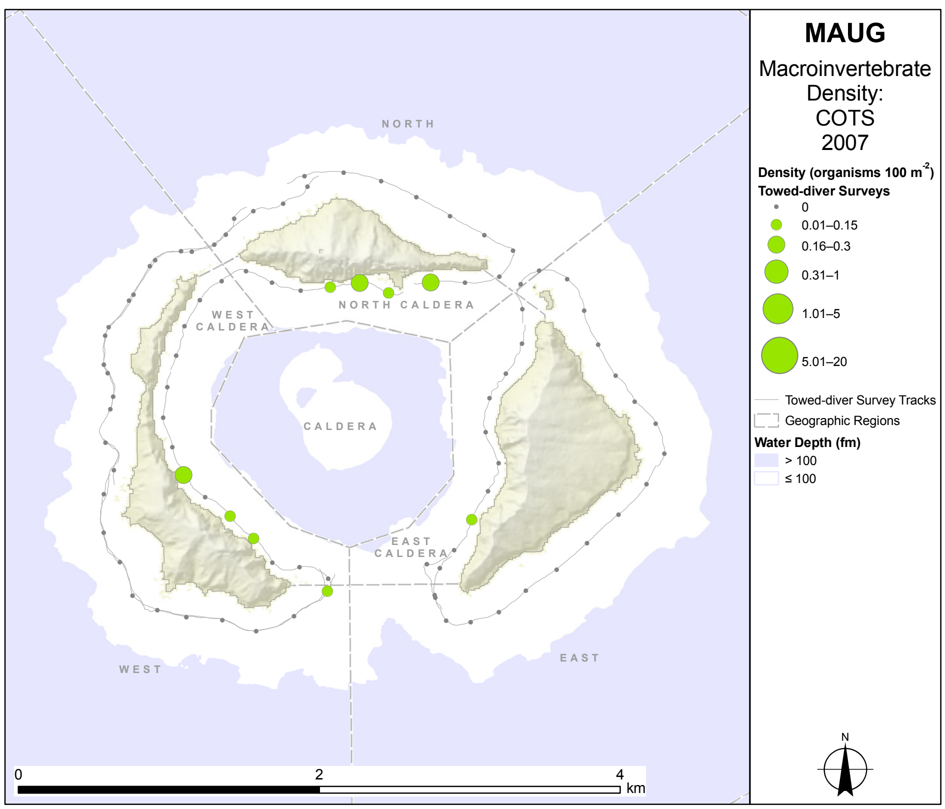


Figure 16.7.1g. Densities (organisms 100 m^{-2}) of COTS from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.



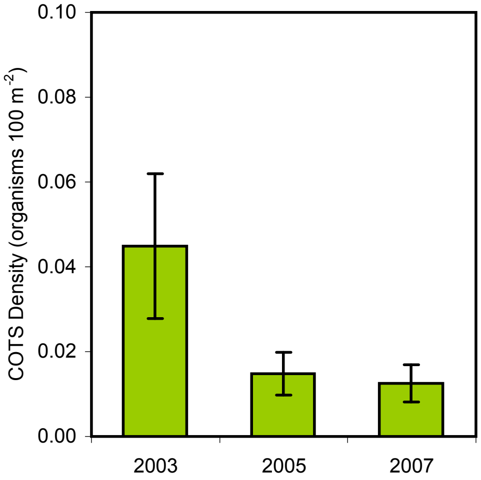


Figure 16.7.1h. Temporal comparison of COTS mean densities (organisms 100 m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested relatively low daytime densities of COTS around Maug during MARAMP 2003, 2005, and 2007, compared to other sites surveyed in the Mariana Archipelago, with the exception of one localized area in 2003. The overall observed mean density of COTS was higher in 2003 than in 2005 and 2007 (Fig. 16.7.1h). Given that these corallivorous seastars can decimate a reef, understanding whether their observed densities signify an outbreak is important. By means of a manta-tow technique—which uses snorkel divers as observers in a manner similar to the procedure established for using scuba divers to conduct MARAMP towed-diver surveys—Moran and De'ath (1992) defined a potential outbreak as a reef area where the density of *A. planci* was > 1500 organisms per km² (0.15 organisms 100 m^{-2}) and the level of dead coral present was at least 40%. Using this definition only in terms of density and considering each towed-diver survey as an individual reef area, only one localized area was found during MARAMP 2003 with relatively high densities of COTS that suggest that they were undergoing an outbreak. This area was in the west caldera region, where densities of COTS from towed-diver surveys were estimated at 0.685 organisms 100 m^{-2}. However, the highest density of COTS was observed in this coral-rich area along the eastern coast of West Island during each of the 3 MARAMP survey years. Therefore, a relatively large COTS population likely resides naturally in this west caldera region, and the observed high densities are not indicative of an outbreak population.

Sea Cucumbers

During MARAMP 2003, sea cucumbers were observed at only 3 of the 8 REA sites surveyed and in 10 of the 16 towed-diver surveys conducted around Maug (Fig. 16.7.1i). The overall mean density of sea cucumbers from REA surveys was 0.5 organisms 100 m^{-2} (SE 0.267), and the overall mean density from towed-diver surveys was 0.028 organisms 100 m^{-2} (SE 0.013). Survey results suggest that sea cucumbers were most abundant at MAU-10 in the west caldera region with 2

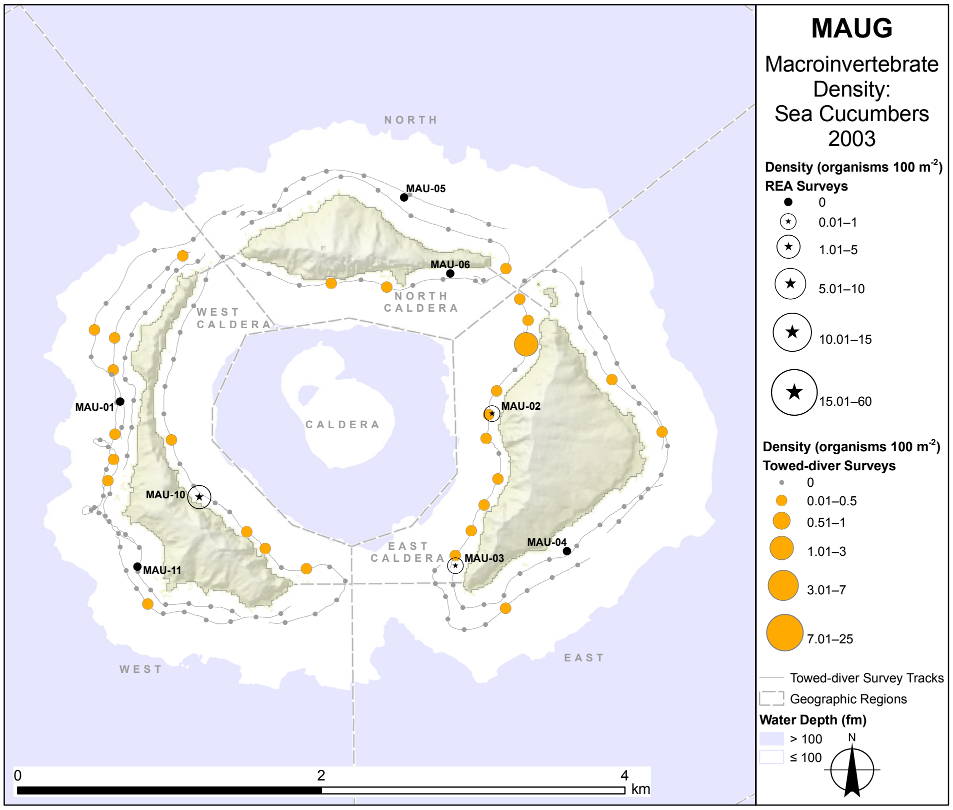
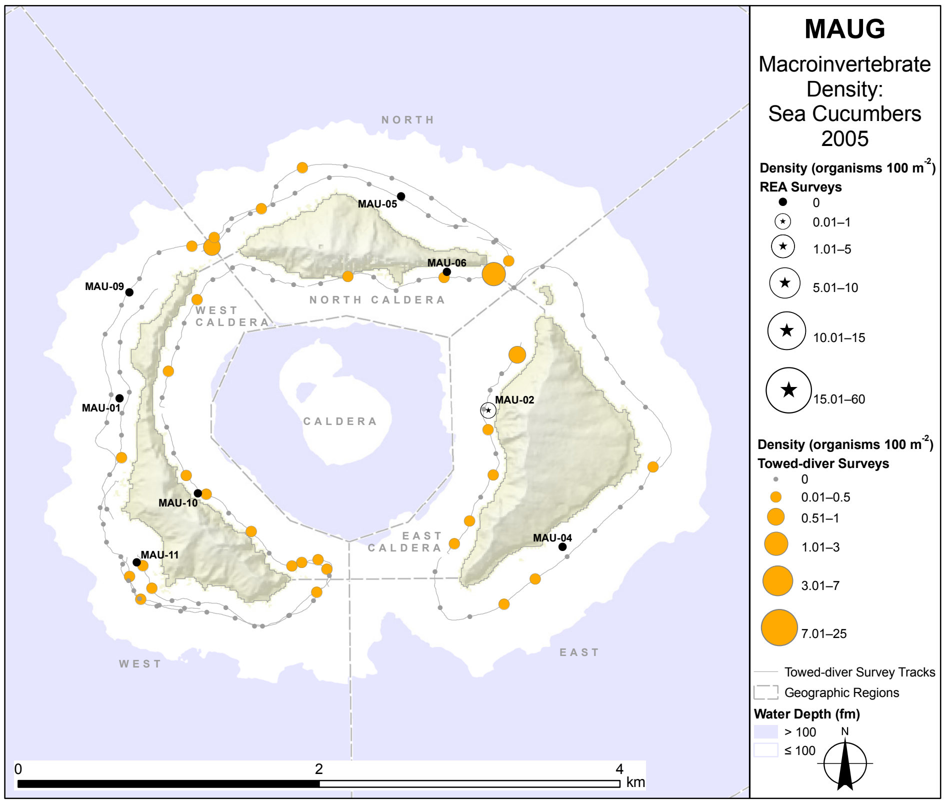


Figure 16.7.1i. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

organisms 100 m^{-2}; both of these sea cucumbers were from the genus *Holothuria*. Among all towed-diver surveys conducted around Maug, the survey completed in the east caldera region had the highest mean density of sea cucumbers with 0.253 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 1.959 organisms 100 m^{-2}.

During MARAMP 2005, sea cucumbers were observed at only 1 of the 8 REA sites surveyed and in 11 of the 13 towed-diver surveys conducted around Maug (Fig.16.7.1j). MAU-02 in the east caldera region had a density of sea cucumbers with 1 organism 100 m^{-2}; this sea cucumber was from the genus *Pearsonothuria.* The overall mean density of sea cucumbers from towed-diver surveys was 0.055 organisms 100 m^{-2} (SE 0.022). Among all towed-diver surveys conducted around Maug, the survey completed in the north caldera region had the highest mean density of sea cucumbers with 0.267 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 2.462 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.150 organisms 100 m^{-2}, recorded around the southern end of West Island; segment densities ranged from 0 to 0.419 organisms 100 m^{-2}.

Figure 16.7.1j. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.



During MARAMP 2007, sea cucumbers were observed at only 1 of the 9 REA sites surveyed but recorded in 10 of the towed-diver surveys conducted around Maug (Fig.16.7.1k). MAU-10 in the west caldera region had a density of 4 organisms 100 m^{-2}, and 83% of these sea cucumbers were from the genus *Holothuria.* Two other genera were represented at Maug: *Actinopyga* and *Pearsonothuria.* The overall mean density of sea cucumbers from towed-diver surveys was 0.043 organisms 100 m^{-2} (SE 0.008). Among all towed-diver surveys conducted around Maug, the survey completed in the east caldera region had the highest density of sea cucumbers with 0.124 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 0.403 organisms 100 m^{-2}. The second-greatest mean density of sea cucumbers from a towed-diver survey was 0.079 organisms 100 m^{-2}, recorded in the west caldera region; segment densities ranged from 0 to 0.343 organisms 100 m^{-2}.

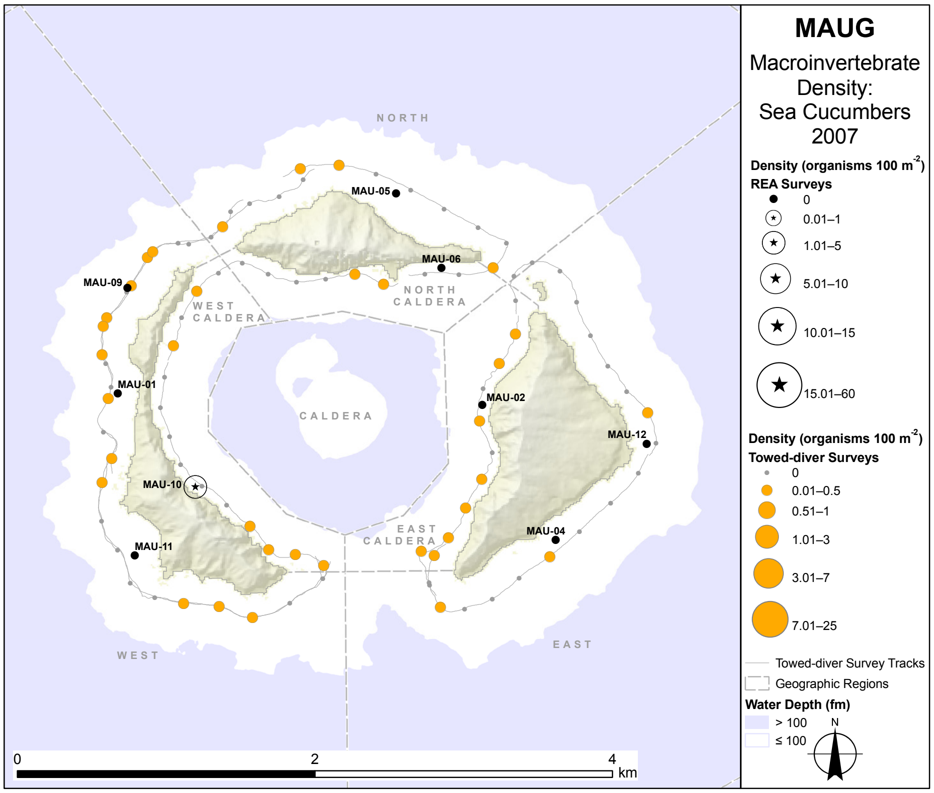


Figure 16.7.1k. Densities (organisms 100 m^{-2}) of sea cucumbers from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.

Towed-diver surveys suggested relatively low daytime abundance of sea cucumbers around Maug during MARAMP 2003, 2005, and 2007 (Fig. 16.7.1l), relative to the rest of the Mariana Archipelago. Although densities were low in the 3 MARAMP survey years, the highest concentrations of sea cucumbers around Maug were observed in the caldera regions. Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea cucumbers (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys").

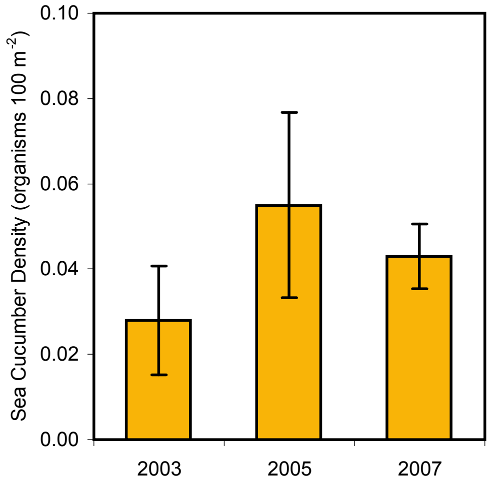


Figure 16.7.1l. Temporal comparison of sea cucumber mean densities (organisms m^{-2}) from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Sea Urchins

During MARAMP 2003, sea urchins were observed at 6 of the 8 REA sites surveyed and in all 16 of the towed-diver surveys conducted around Maug (Fig. 16.7.1m). The overall mean density of sea urchins from REA surveys was 18.37 organisms 100 m^{-2} (SE 10.68), and the overall mean density from towed-diver surveys was 4.70 organisms 100 m^{-2} (SE 0.89). Survey results suggest that sea urchins were most abundant at MAU-05 in the north region with 76 organisms 100 m^{-2}. Rock-boring urchin species from the genus *Echinostrephus* were the dominant macroinvertebrates at this site, accounting for 79% of urchins recorded. Other genera represented at this site included *Echinothrix* and *Echinometra.* MAU-04 in the east region had the second-greatest density with 57 organisms 100 m^{-2}. Also at this site, rock-boring urchin species from the genus *Echinostrephus* were the dominant macroinvertebrates, accounting for 87.7% of sea urchins recorded. Species of *Echinothrix* were also observed at MAU-04.

Among all towed-diver surveys conducted around Maug in 2003, the survey completed in the east region had the highest mean density of 27.85 organisms 100 m^{-2}; segment densities from this survey ranged from 10.38 to 49.41 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 23.03 organisms 100 m^{-2}, recorded along the southwestern shore of West Island; segment densities ranged from 0 to 55.13 organisms 100 m^{-2}.

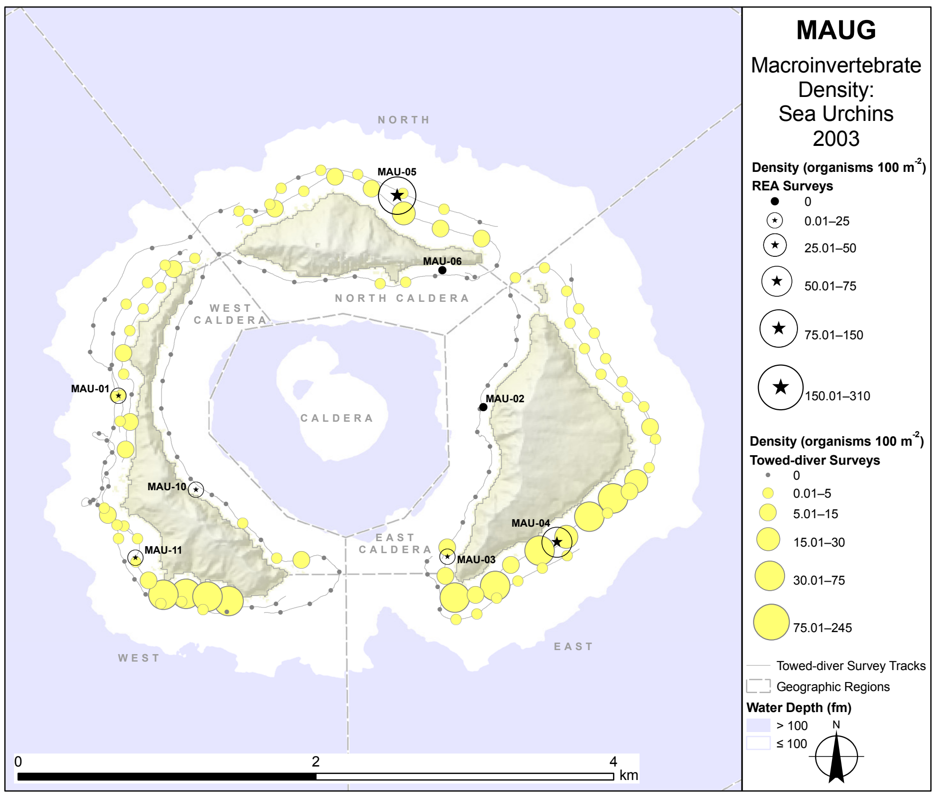


Figure 16.7.1m. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003.

During MARAMP 2005, sea urchins were observed at 5 of the 8 REA sites surveyed and in 10 of the 13 towed-diver surveys conducted around Maug (Fig. 16.7.1n). The overall mean density from REA surveys was 2.5 organisms 100 m^{-2} (SE 1.24), and the overall mean density from towed-diver surveys was 3.97 organisms 100 m^{-2} (SE 0.97). Survey results suggest that sea urchins were most abundant at MAU-04 in the east region with a mean density of 9 organisms 100 m^{-2}, with 79% of these sea urchins belonging to the rock-boring genus *Echinostrephus*. Species of *Echinothrix* were also observed at MAU-04.

Among all towed-diver surveys conducted around Maug in 2005, the survey completed along the southwestern coast of West Island had the highest mean density of sea urchins with 19.45 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 64.57 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 18.49 organisms 100 m^{-2}, recorded in the north region; segment densities ranged from 0 to 42.64 organisms 100 m^{-2}.

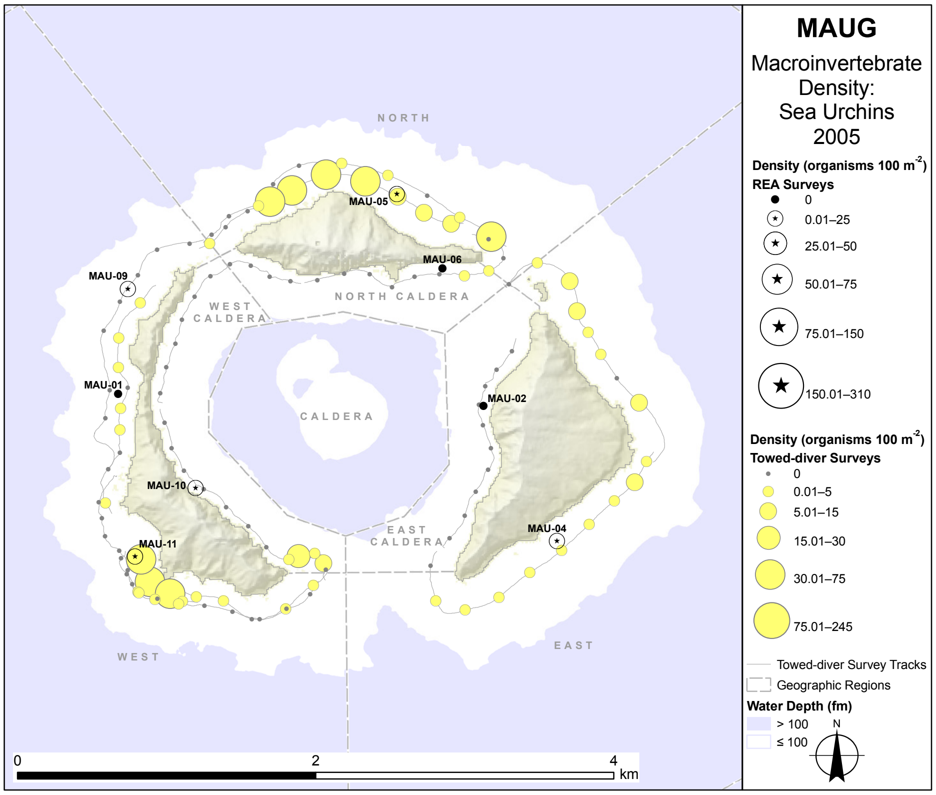


Figure 16.7.1n. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005.

During MARAMP 2007, sea urchins were observed at 6 of the 9 REA sites surveyed and in 8 of 10 towed-diver surveys conducted around Maug (Fig. 16.7.1o). The overall mean density for REA surveys was 16.96 organisms 100 m^{-2} (SE 10.78), and the overall mean density from towed-diver surveys was 1.83 organisms 100 m^{-2} (SE 0.31). Survey results suggest that sea urchins were most abundant at MAU-04 in the east region with 100.33 organisms 100 m^{-2}, with 99% of these

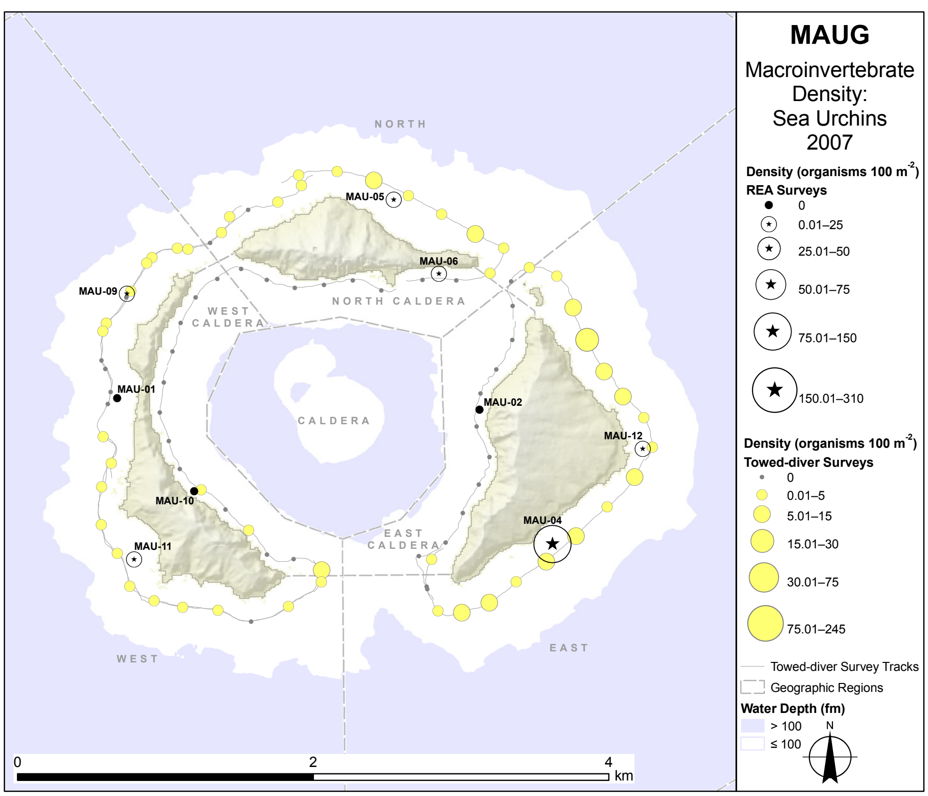


Figure 16.7.1o. Densities (organisms 100 m^{-2}) of sea urchins from REA and towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007.

sea urchins belonging to the rock-boring genus *Echinostrephus.* MAU-05 had the second-greatest density of sea urchins with 22.33 organisms 100 m^{-2}, with 98% of these sea urchins also belonging to the rock-boring genus *Echinostrephus.* The only other genus represented from REA surveys was *Echinothrix.*

Among all towed-diver surveys conducted around Maug in 2007, the survey completed along the southeastern coast of East Island had the highest mean density of sea urchins with 5.28 organisms 100 m^{-2}; segment densities from this survey ranged from 0 to 14.05 organisms 100 m^{-2}. The second-greatest mean density of sea urchins from a towed-diver survey was 5.25 organisms 100 m^{-2}, recorded along the northeastern coast of East Island; segment densities ranged from 0 to 15.56 organisms 100 m^{-2}.

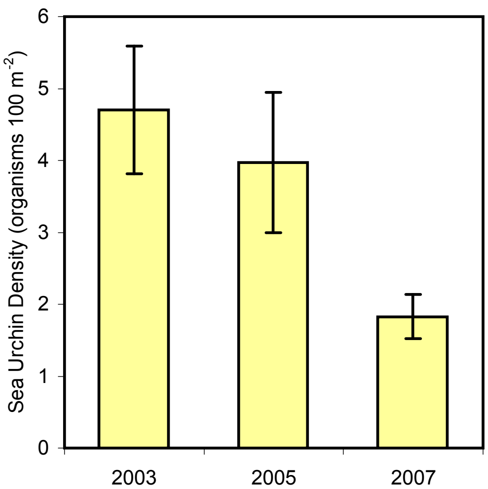


Figure 16.7.1p. Temporal comparison of mean densities (organisms m^{-2}) of sea urchins from towed-diver benthic surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Towed-diver surveys suggested low daytime abundance of sea urchins around Maug, compared to the rest of the Mariana Archipelago, with the exception of the survey areas along the southern coasts of both East and West Islands and in the north region. The overall observed mean density of sea urchins was lower in 2007 than in 2003 and 2005 (Fig. 16.7.1p). Minor fluctuations in densities are not necessarily indicative of changes in the population structure of sea urchins (for information about data limitations, see Chapter 2: "Methods and Operational Background," Section 2.4: "Reef Surveys"). The highest sea urchin densities around Maug were observed during the MARAMP 2003 and 2005 towed-diver surveys conducted the closest to shore. These shallower surveys were not repeated during MARAMP 2007, and this change in survey effort is a likely cause of the observed decline in overall sea urchin density in 2007.

16.8 Reef Fishes

16.8.1 Reef Fish Surveys

Large-fish Biomass

During MARAMP 2003, 16 towed-diver surveys for large fishes (≥ 50 cm in total length [TL]) were conducted in forereef habitats around the islands of Maug. Surveys circumnavigated all 3 of the islands that compose Maug, and multiple surveys were conducted on the forereef slopes at Maug (Fig. 16.8.1a). The overall estimated mean biomass of large fishes around Maug, calculated as weight per unit area, was 1.61 kg 100 m^{-2} (SE 0.31), a moderately high value compared to other survey areas in the Mariana Archipelago. Snappers (Lutjanidae) and sharks (Carcharhinidae and Ginglymostomatidae) contributed 39% and 30% (0.62 and 0.49 kg 100 m^{-2}) of overall large-fish biomass. The twinspot snapper (*Lutjanus bohar*) was the major snapper species by biomass, while the grey reef shark (*Carcharhinus amblyrhynchos*) was the major shark species. Of the 90 sharks observed in 2003, 61 were grey reef sharks. Other shark species recorded were the whitetip reef shark (*Triaenodon obesus*) and tawny nurse shark (*Nebrius ferrugineus*). Observed large-fish biomass was highest in the east region, where sharks and snappers were common. Additionally, a large school of bigeye trevally (*Caranx sexfaciatus*) was observed in the north region with numerous individuals exhibiting spawning behavior.

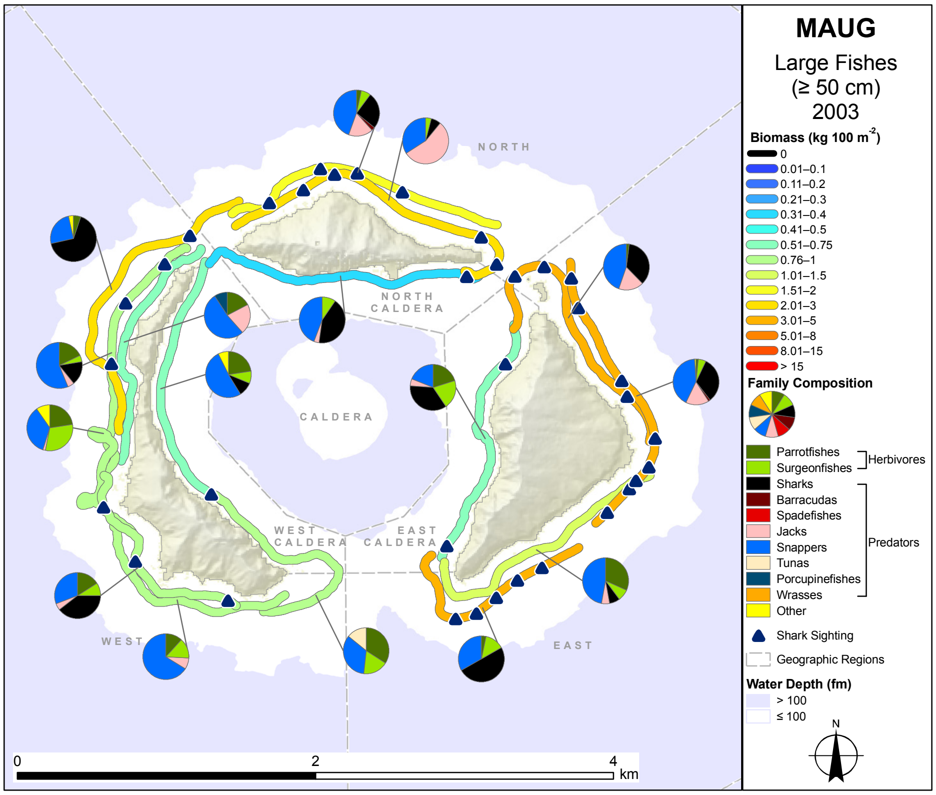


Figure 16.8.1a. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2003. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.

During MARAMP 2005, 12 towed-diver surveys for large fishes (≥ 50 cm TL) were conducted in forereef habitats around Maug. The overall estimated mean biomass of large fishes around these islands was 0.85 kg 100 m^{-2} (SE 0.16). Reef sharks and jacks (Carangidae) contributed 53% and 19% (0.45 and 0.16 kg 100 m^{-2}) of overall mean large-fish biomass. In 2005, 86 sharks were observed, primarily on the outer flanks of these islands, and the most abundant shark species were the

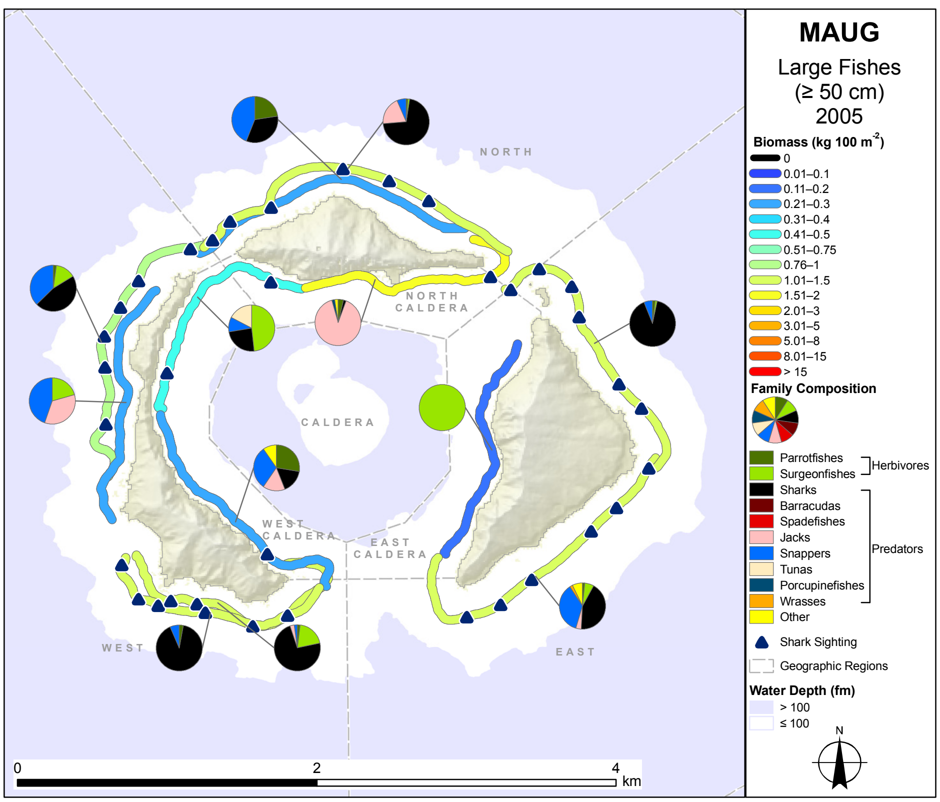
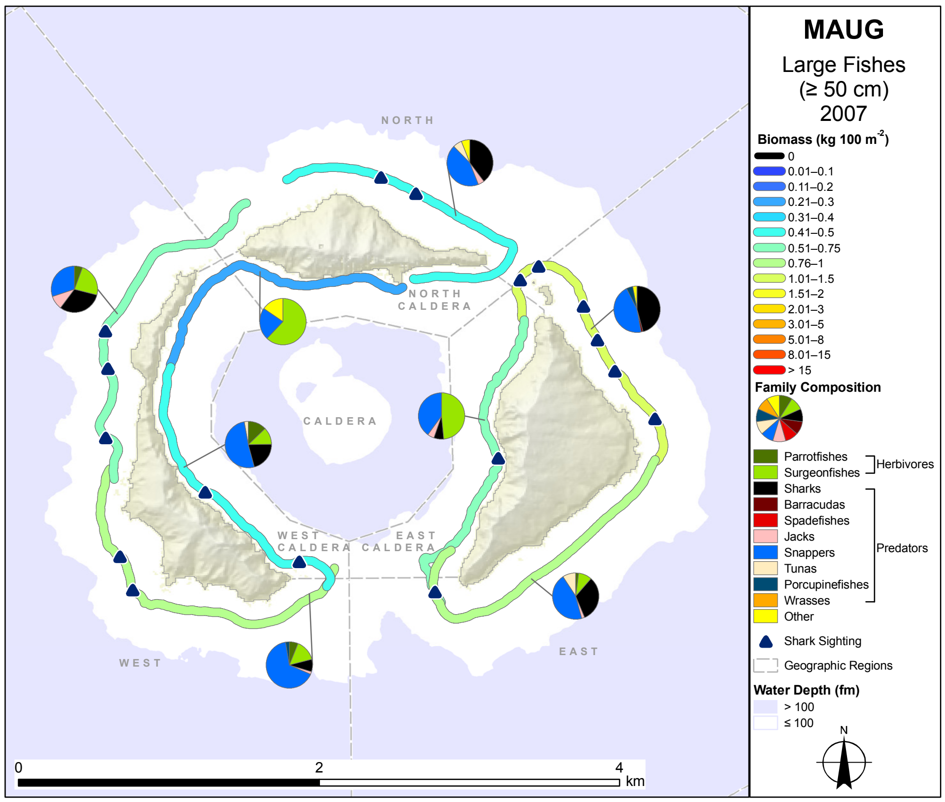


Figure 16.8.1b. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2005. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.

whitetip reef shark and grey reef shark (Fig. 16.8.1b). The bigeye trevally was the major jack species by biomass, a result of the sighting of a large school in the channel between North and East Islands (for place-names and their locations, see Figure 16.2a in Section 16.2: “Survey Effort”). The twinspot snapper and black-and-white snapper (*Macolor niger*) were also common in 2005.

During MARAMP 2007, 9 towed-diver surveys for large fishes (≥ 50 cm TL) were conducted in forereef habitats around Maug (Fig. 16.8.1c). The overall estimated mean biomass of large fishes around these islands was 0.72 kg 100 m^{-2} (SE 0.11). Reef sharks and snappers together contributed 67% or 0.48 kg 100 m^{-2} of overall large-fish biomass. Snappers alone accounted for 38% of overall large-fish biomass, and the twinspot snapper had the highest biomass among the species in that family observed at Maug. Reef sharks accounted for 20% of overall mean large-fish biomass, dominated by the whitetip reef shark with 20 individuals observed. Ten grey reef sharks also were observed in 2007. Other notable observations included sightings of dogtooth tuna (*Gymnosarda unicolor*) and large, planktivorous surgeonfishes (Acanthuridae), such as the sleek unicornfish (*Naso hexacanthus*) seen along steep slopes of the outer flanks of Maug.

Figure 16.8.1c. Observations of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}), family composition, and shark sightings from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2007. Each blue triangle represents a sighting of one or more sharks recorded inside or outside of the survey area over which they are shown.



Overall large-fish biomass around Maug was about average for the unpopulated islands in the Mariana Archipelago, based on values recorded during towed-diver surveys of forereef habitats. Observed biomass declined from 1.61 kg 100 m^{-2} (SE 0.31) in 2003 to 0.72 kg 100 m^{-2} (SE 0.11) in 2007 (Fig. 16.8.1d). Reef sharks contributed the largest percentage of overall mean biomass of large fishes, and the whitetip reef shark was the most common shark species observed in the 3 MARAMP survey years. A large school of bigeye trevally was observed in 2003 and 2005. Notable observations included sightings of the rare giant grouper (*Epinephelus lanceolatus*) and scalloped hammerhead shark (*Sphyrna lewini*), both observed in 2003; however, both species were observed off transect and were not recorded during the quantitative surveys. No humphead wrasse (*Cheilinus undulatus*) or bumphead parrotfish (*Bolbometopon muricatum*) were observed during the 3 MARAMP survey periods.

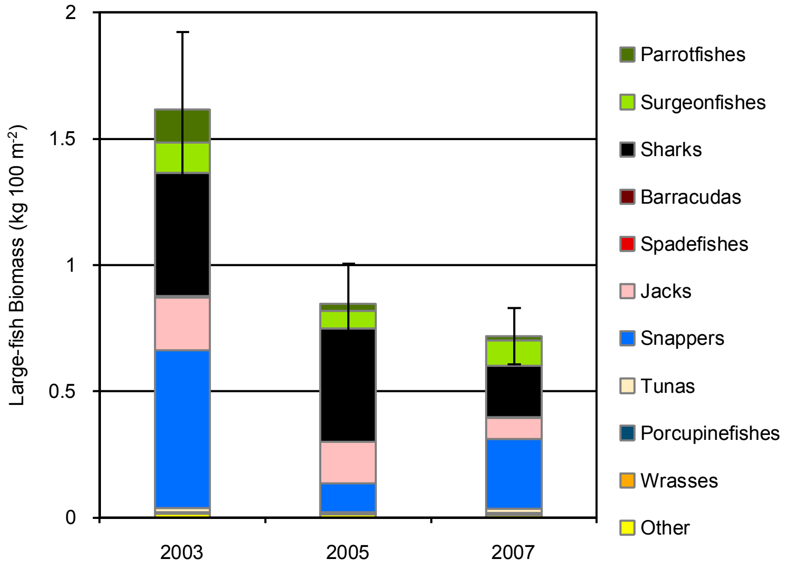


Figure 16.8.1d. Temporal comparison of mean values of large-fish (≥ 50 cm in TL) biomass (kg 100 m^{-2}) from towed-diver fish surveys of forereef habitats conducted around Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

Total Fish Biomass and Species Richness

Total fish biomass for the 8 REA sites surveyed in forereef habitats at Maug during MARAMP 2003 was moderately high compared to other sites in the Mariana Archipelago with an overall sample mean of 7.80 kg 100 m^{-2} (SE 3.13). The highest biomass of 28.78 kg 100 m^{-2} was seen at MAU-03 in the east region (Fig. 16.8.1e). Fusiliers (Caesionidae) accounted for 33% or 2.56 kg 100 m^{-2} of total fish biomass at Maug. The yellow and blueback fusilier (*Caesio teres*) was the most abundant fusilier species with large schools of this planktivore observed at MAU-02 and MAU-03 in the east region. The only shark species observed in 2003 was the whitetip reef shark, with 3 individuals recorded.

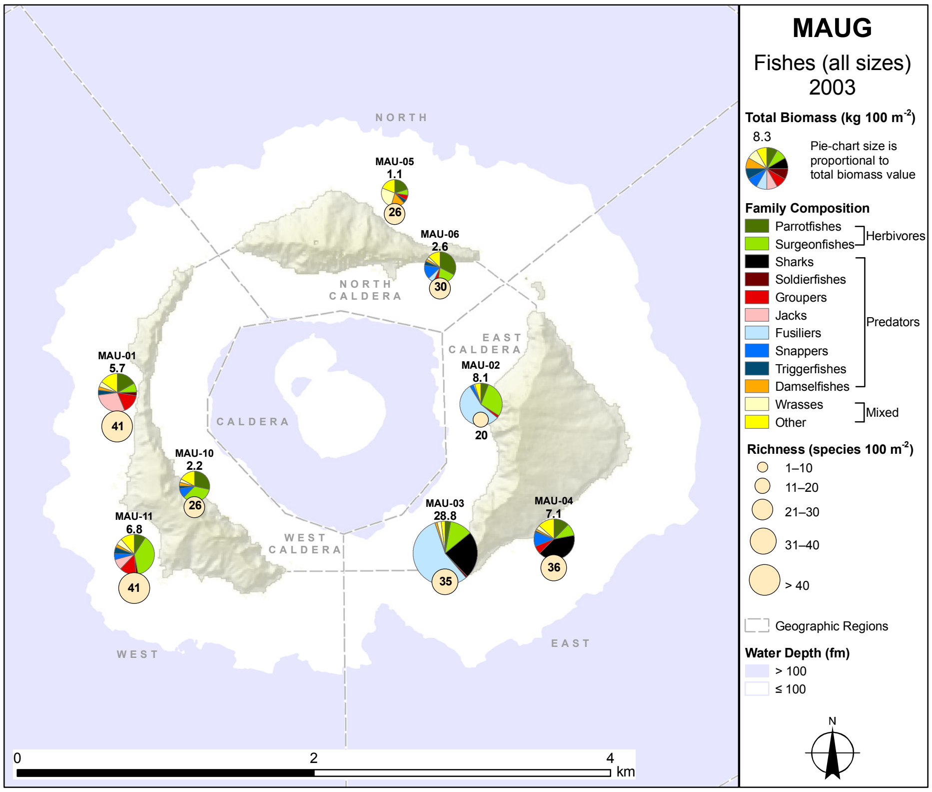


Figure 16.8.1e. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2003.

Based on REA surveys conducted during MARAMP 2003, species richness at Maug ranged from 20 to 41 species 100 m^{-2}. The lowest diversity was seen at MAU-02 in the east caldera region, while the highest diversity was found at MAU-01 and MAU-11 in the west region. Damselfishes (Pomacentridae) composed the most abundant fish family with Vanderbilt's chromis (*Chromis vanderbilti*), midget chromis (*Chromis acares*), and agile chromis (*Chromis agilis*) dominating count estimates. Additionally, the orangespine unicornfish (*Naso lituratus*) was the fourth-most abundant fish species seen at Maug, a result likely due in part to a recent recruitment.

Total fish biomass for the 8 REA sites surveyed in forereef habitats at Maug during MARAMP 2005 was similar to estimates in 2003 with an overall sample mean of 7.16 kg 100 m^{-2} (SE 1.19). The highest biomass of 13.57 kg 100 m^{-2} was seen at MAU-01 in the west region (Fig. 16.8.1f). Surgeonfishes contributed 35% or 2.54 kg 100 m^{-2} of total fish biomass at Maug. The orangespine unicornfish accounted for 32% of surgeonfish biomass. The whitecheek surgeonfish (*Acanthurus nigricans*) was the most abundant surgeonfish species observed with a mean of 8 individuals 100 m^{-2}. Reef sharks were rare, with only 1 whitetip reef shark observed at MAU-10 in 2005.

Based on REA surveys conducted during MARAMP 2005, species richness at Maug ranged from 27 to 40 species 100 m^{-2}. The lowest diversity was seen at MAU-10 in the west caldera region, and the highest diversity levels were found at MAU-11 and MAU-01 in the west region. Wrasses (Labridae), damselfishes, and surgeonfishes composed the most represented families with 28, 17, and 17 species recorded. The midget chromis was the most abundant species with an overall mean density of 39 individuals 100 m^{-2}.

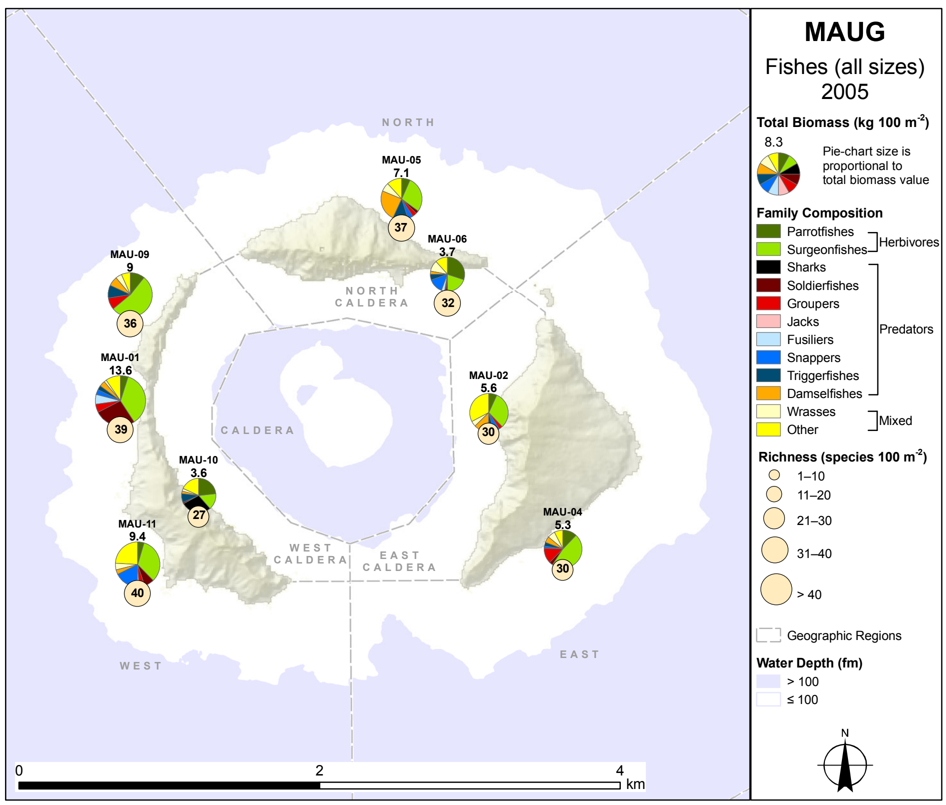


Figure 16.8.1f. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2005.

Total fish biomass for the 9 REA sites surveyed in forereef habitats at Maug during MARAMP 2007 was moderate compared to other sites in the Mariana Archipelago with an overall sample mean of 6.60 kg 100 m^{-2} (SE 1.51). Similar to observations made in 2005, surgeonfishes accounted for the largest proportion (38%) or 2.52 kg 100 m^{-2} of total fish biomass at Maug (Fig. 16.8.1g). The orangespine unicornfish accounted for 29% of surgeonfish biomass. Snappers were also common, contributing 10% of total fish biomass at Maug. The twinspot snapper accounted for 89% of observed snapper biomass. Large predators were rare except at MAU-12 on the outer flank in the east region, where 2 whitetip reef sharks and 1 giant trevally (*Caranx ignobilis*) were observed.

Based on REA surveys conducted during MARAMP 2007, species richness at Maug ranged from 27 to 38 species 100 m^{-2}. The highest diversity was seen at MAU-09 in the west region, and the lowest diversity was found at the 3 sites in the caldera regions: MAU-02, MAU-06, and MAU-10. Damselfishes were by far the most abundant fishes, and the midget chromis and Vanderbilt's chromis dominated counts with overall mean densities of 77 and 59 individuals 100 m^{-2}.

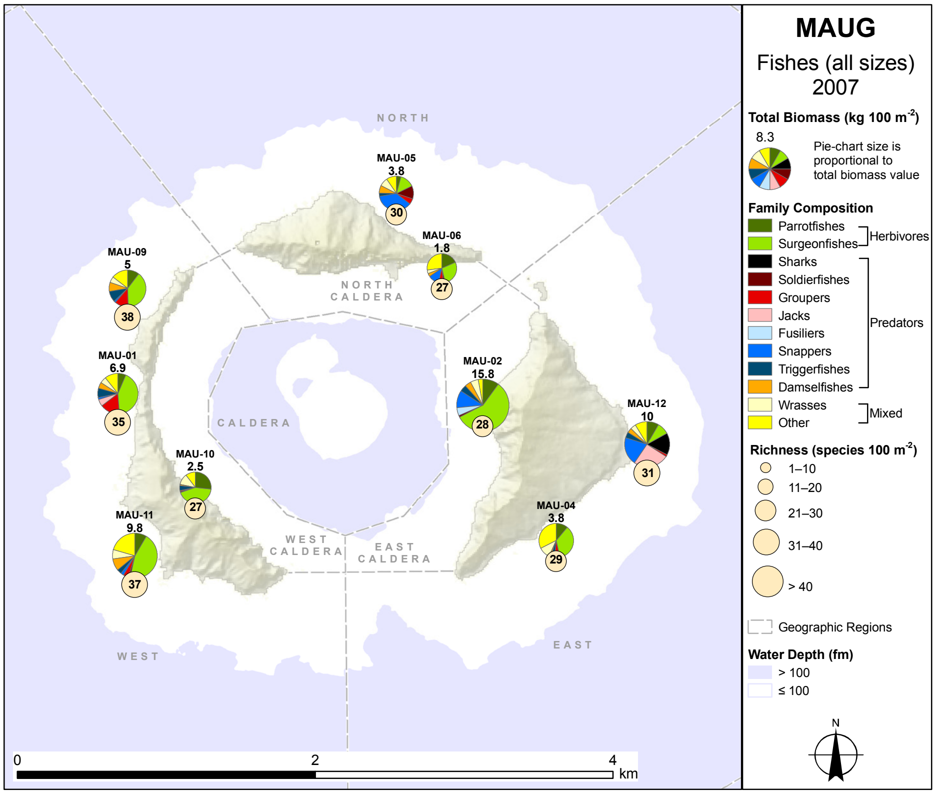


Figure 16.8.1g. Observations of total fish biomass (all species and size classes in kg 100 m^{-2}), family composition, and species richness (species 100 m^{-2}) from REA fish surveys using the belt-transect method in forereef habitats at Maug during MARAMP 2007.

No clear spatial patterns in total fish biomass were observed at Maug between the 3 MARAMP survey years. In general, overall mean total fish biomass was moderately low compared to estimates from other remote, uninhabited islands in the northern part of the Mariana Archipelago. Mean values of total fish biomass were similar over the 3 survey periods, ranging from 7.80 kg 100 m^{-2} (3.13 SE) in 2003 to 6.60 kg 100 m^{-2} (1.51 SE) in 2007 (Fig. 16.8.3h). Large predatory species, such as reef sharks, were rare during REA surveys with only 6 whitetip reef sharks observed over the 3 survey years. A likely recruitment pulse of the orangespine unicornfish was observed in 2003. The initial recruitment carried over into the following survey years with the orangespine unicornfish accounting for ~ 11% of the overall mean fish biomass in 2005 and 2007.

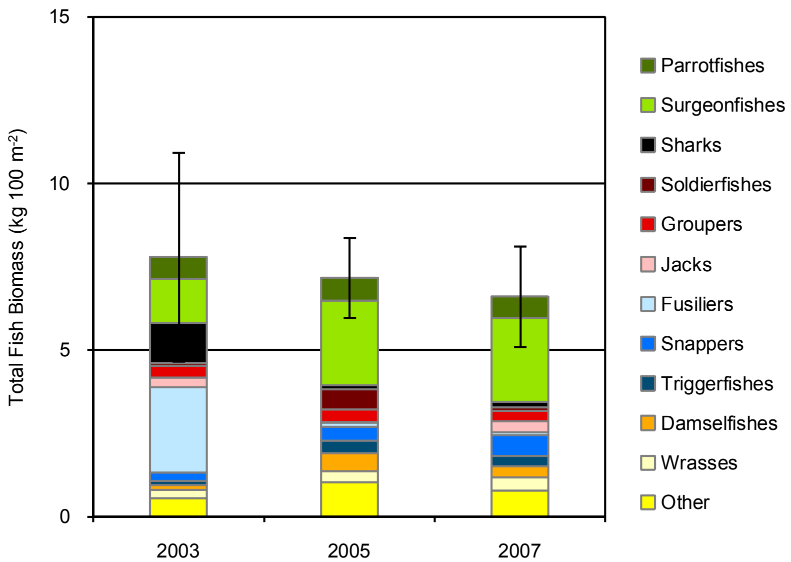


Figure 16.8.1h. Temporal comparison of mean values of total fish biomass (all species and size classes in kg 100 m^{-2}) from REA fish surveys of forereef habitats conducted at Maug during MARAMP 2003, 2005, and 2007. Error bars indicate standard error (± 1 SE) of the mean.

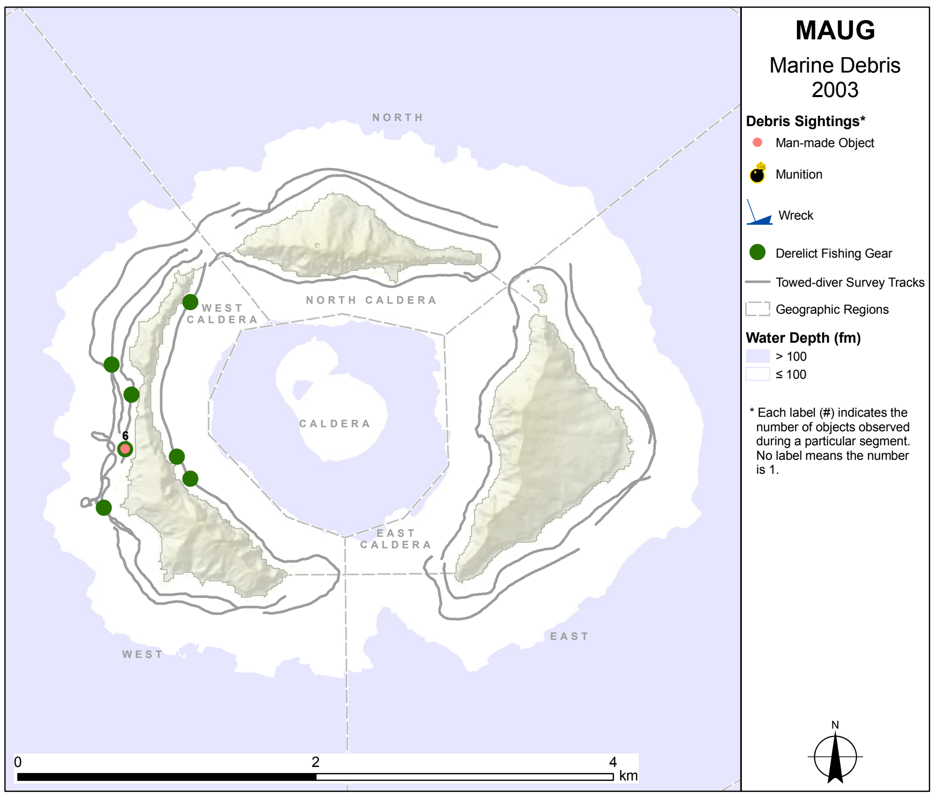
Species richness for the 3 MARAMP survey periods was highest at the forereef sites located on the outer flanks in the west region. These seaward-facing sites in the west region had the highest mean species richness of 37 species 100 m^{-2}. Wrasses, damselfishes, and surgeonfishes were well represented with high species diversity among REA sites. Damselfishes were the most abundant fish taxa, and the midget chromis and Vanderbilt's chromis dominated counts.

16.9 Marine Debris

16.9.1 Marine Debris Surveys

During MARAMP 2003, 7 sightings of derelict fishing gear and 5 sightings of other man-made objects were recorded in the 16 towed-diver surveys conducted on forereef habitats around the islands of Maug (Fig. 16.9.1a). Of the 7 sightings involving fishing nets or lines, 4 were recorded in the west region and 3 in the west caldera region. The 5 man-made objects were observed during a single survey segment in the west region. No munitions or wrecks were identified.

Figure 16.9.1a. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2003. Symbols indicate the presence of specific debris types.



During MARAMP 2005, 2 sightings of derelict fishing gear were recorded in the 13 towed-diver surveys conducted on forereef habitats around Maug (Fig. 16.9.1b). Fishing lines were observed in the east caldera and west caldera regions. No munitions, wrecks, or other man-made objects were identified.

During MARAMP 2007, 2 sightings of derelict fishing gear were recorded in the 11 towed-diver surveys conducted on forereef habitats around Maug (Fig. 16.9.1c). One fishing line was observed in the east caldera region, and a net was seen inside of the channel entrance between the east caldera and east regions. No munitions, wrecks, or other man-made objects were identified.

Observations of debris are positive identifications, but absence of reports does not imply lack of debris. Since methods for observing marine debris varied between MARAMP surveys in 2003, 2005, and 2007, temporal comparisons are not appropriate. Debris sightings were recorded differently—with sightings in 2003 recorded as a direct part of diver observational methods and sightings in 2005 and 2007 recorded solely as incidental observations by the towed divers in their observer comments. No locations of marine debris sightings at Maug overlapped between 2005 and 2007.

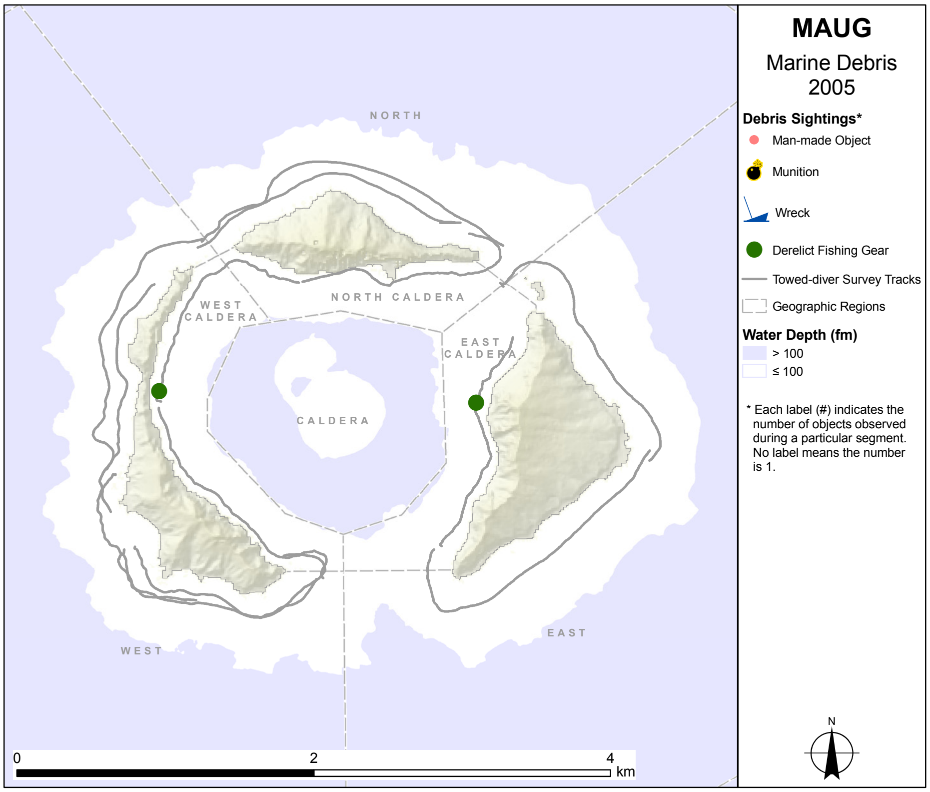


Figure 16.9.1b. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2005. Symbols indicate the presence of specific debris types.

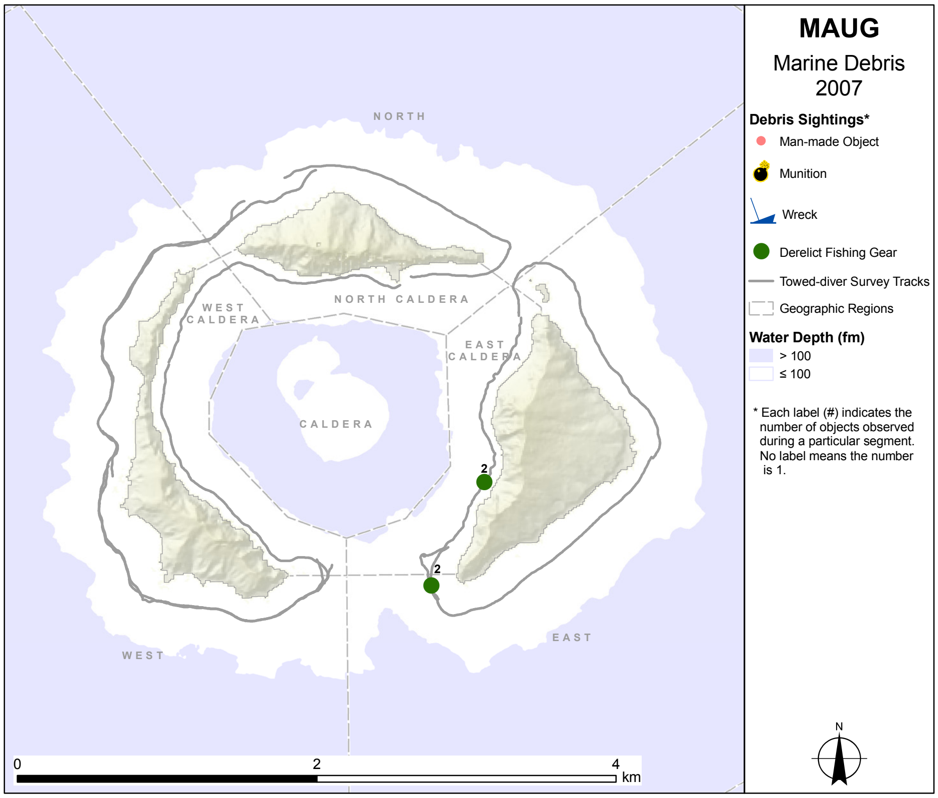


Figure 16.9.1c. Qualitative observations of marine debris from towed-diver benthic surveys of forereef habitats conducted around Maug during MARAMP 2007. Symbols indicate the presence of specific debris types.

16.10 Ecosystem Integration

The spatial distributions and temporal patterns of individual coral reef ecosystem components around the islands of Maug are discussed in the discipline-specific sections of this chapter. In this section, key ecological and environmental aspects are considered concurrently to identify potential relationships between various ecosystem components both inside the caldera of Maug and on the outer flanks of these islands. In addition to this island-level analysis, evaluations across the entire Mariana Archipelago are presented in Chapter 3: "Archipelagic Comparisons," including archipelago-wide reef condition indices with ranks for Maug as well as the other 13 islands covered in this report.

Maug is unique among the islands of the Mariana Archipelago in its geomorphology. All northern islands and banks have been created by volcanic activity, but Maug's crater rim has been breached by the sea, producing a submerged, flooded caldera that is 2 km in diameter and connected to the open ocean by 3 narrow channels. This distinctive feature creates unusual conditions that, as observed during MARAMP surveys, supported a diversity of habitats that was greater around Maug than around the other northern islands in the Mariana Archipelago. Ongoing subsurface hydrothermal venting activity within the caldera of Maug has augmented this habitat diversity.

Inside the Caldera

The inner slopes of the 3 islands of Maug, formed by caldera walls, are all very steep. Underwater, these steep slopes plunge to depths > 200 m and then rise again in the center of this small caldera to depths < 20 m. The nearshore slopes of Maug are less steep in the 3 areas where the crater rim has slumped and created channels that separate these islands. The steep slopes within this volcanic crater provide a protected environment that, based on MARAMP results from towed-diver and REA surveys, generally supported live-hard-coral cover > 10%, with a few exceptions that included the 2 areas of silt adjacent to the channels that separate North Island from West and East Islands (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"). Many areas of this protected environment were dominated by the coral genus *Goniastrea*, species of which grow on steep walls, providing a framework for other corals and invertebrates. Also numerically abundant were the genera *Porites* and *Astreopora*.

Figure 16.10a. Hydrothermal vents release gas bubbles, warm water at a site west of East Island. "Fluffy" silt that is brown, orange, and yellow-tinted covers the seafloor. *NOAA photo*

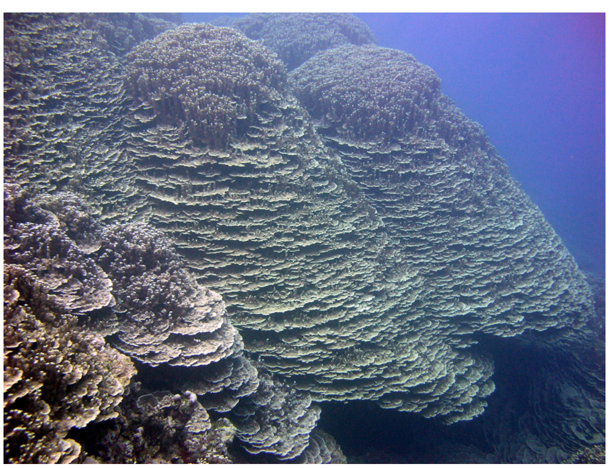


Figure 16.10b. *Porites rus* seen on the west coast of East Island at REA site MAU-02, where the genus *Porites* was a dominant part of the coral reef assemblage in 2005 and 2007. *NOAA photo*

Another uncommon feature of Maug was the presence of hydrothermal vents in its caldera. For all of the other shallow-water coral reefs surveyed in the Mariana Archipelago, observed hydrothermal activity was restricted to land. West of East Island in the northern part of the east caldera region, divers observed vents releasing warm water and gas bubbles. Divers surveying at this hydrothermal vent system found water temperatures of 48°C–63°C, pH of 6.09, TA of 3.56, and an undersaturated aragonite saturation state of 0.25. The seafloor surrounding these vents was littered with boulders and rubble, presumably from a previous landslide, with every surface covered with a layer of "fluffy" silt that was brown, orange, and yellow-tinted (Fig. 16.10a). No benthic surveys were conducted at this vent system, so precise values for this site are not presented in this report. However, a REA survey conducted at MAU-02 only 15 m south of this vent site revealed levels of live coral cover that were on average very high: 67% in 2007. The genus *Porites* was a dominant component of the coral reef assemblage at MAU-02 (Fig. 16.10b) in both MARAMP 2005 and 2007, having a much higher relative abundance at MAU-02 than at any other REA site surveyed at Maug (see Figures 16.5.1j, k, and l in Section 16.5.1: "Coral Surveys").

Outer Flanks

The outer flanks of Maug are characterized by the steep slopes typical of the northern islands in the Mariana Archipelago. The presence of a number of volcanic dikes that protrude many meters seaward from these island slopes increase habitat complexity by providing vertical relief. During towed-divers surveys, high concentrations of sea fans, other gorgonians, and corals were recorded.

In 2 areas where multiple towed-diver surveys were conducted, northeast of East Island and west of West Island, observed coral cover was higher in the outer surveys conducted at depths of 10–28 m than in the adjacent, inner surveys conducted at depths < 10 m. The inner surveys primarily documented rock and boulder habitat that presumably originated from landslides. Live coral cover was lower and a macroalgal cover was higher on these shallower habitats than on the deeper survey areas on the outer flanks, where habitats of spur-and-groove, continuous reef were recorded (Fig. 16.10c; also see Figures 16.5.1a, c, and e in Section 16.5.1: “Coral Surveys” and Figure 16.6.1a in Section 3.6.1: “Algal Surveys”). These outer survey areas also supported a higher biomass of large fishes (≥ 50 cm in TL) than did the adjacent surveys in shallower waters (Figs. 16.8.1a, b, and c in Section 16.8.1: “Reef Fish Surveys”).

Towed-diver surveys conducted west of West Island at depths of 12–23 m consistently recorded some of the highest levels of live coral cover observed anywhere around Maug, with a range of 30%–75% in most survey segments (Figs. 16.10c and 16.5.1a, c, and e). This same area—characterized as high relief spur-and-groove habitat, interspersed with canyons and walls—also supported consistently low cover of macroalgae in MARAMP 2003, 2005, and 2007, compared to other areas surveyed in the Mariana Archipelago. COTS and stressed-coral cover were not observed in this area. Data from an STR deployed at a depth of 10 m just south of this survey area show rapid (return periods of 12–24 h) drops (1°C–3°C) in temperature, likely a result of local internal tides. Internal tides were likely formed when tidal currents interacted with steep subsurface topography, causing high-frequency variability in temperature and concentrations of dissolved nutrients and suspended particles. This vertical uplift of subsurface waters off the west coast of West Island, as observed in STR data, was likely affecting the benthic coral reef community in this area.

In contrast to the western flanks of Maug, the exposures south of West and East Islands had consistently low cover of live hard corals recorded during towed-diver surveys in the 3 MARAMP survey years, compared to other areas surveyed around Maug. Live coral cover of < 30% was observed in all but 5 segments of surveys conducted at depths of 5–20 m on these southern flanks. REA survey results also suggest low abundance with live coral cover of 19% at MAU-11 on the southwestern coast of West Island and 9% at MAU-04 on the southeastern coast of East Island in 2007. These habitats were dominated by boulders and supported high macroalgal cover, reaching 75%–100% in some locations, relative to other areas surveyed around Maug (Fig. 16.6.1a in Section 16.6.1: “Algal Cover”). The complexity of these habitats generally was slightly lower than the complexity observed at other survey areas around Maug (Fig. 16.3.3b in Section 16.3.3: “Habitat Characterization”). The south-facing shores of the islands of Maug are also subject to large episodic waves, primarily generated by typhoons that occur on annual to interannual time scales. Along with underlying geology, these large wave events can influence the types of habitats supported along the southern coasts.

Fish Community

In addition to the benthic features described previously, Maug also supported a fish community with medium to high levels of fish biomass and species richness, as observed in both towed-diver surveys of large fishes and REA surveys of fishes of all sizes, compared to the rest of the Mariana Archipelago (see Chapter 3: “Archipelagic Comparisons,” Section 3.7: “Reef Fishes” for more details). Reef sharks were observed in towed-diver surveys during each of the 3 MARAMP survey years. In addition, a number of rare species—including the giant grouper (*Epinephelus lanceolatus*) and scalloped hammerhead shark (*Sphyrna lewini*)—were recorded at Maug that were otherwise seen only at a small number of survey locations in the Mariana Archipelago. However, despite the remote location of Maug and the protection offered by the Commonwealth Constitution (Article XIV, Section 2) since 1978, derelict fishing gear was observed during the 3 survey years, suggesting that reef-fish communities may not have been fully protected from fishing activities in the past.

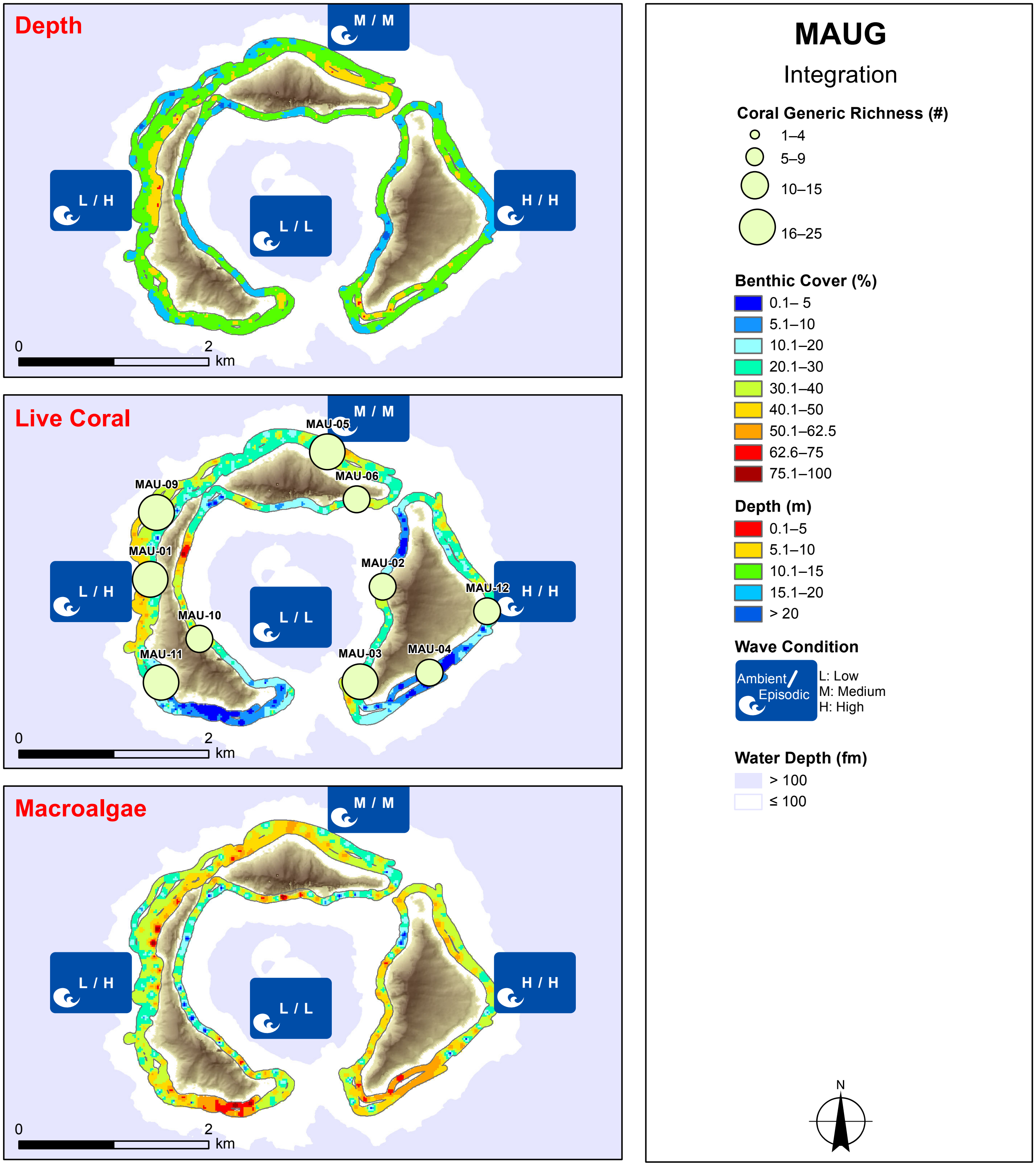


Figure 16.10c. Observations of depth (m), live coral cover (%), and macroalgal cover (%) from towed-diver surveys and coral generic richness from REA surveys conducted on forereef habitats around Maug during MARAMP 2003, 2005, and 2007. Values of depth, coral cover, and macroalgal cover represent interpolated values from the 3 MARAMP survey years, and generic-richness values represent averages of data from the 3 survey years. A large, blue icon indicates the level of ambient and episodic wave exposure for each geographic region.

16.11 Summary

MARAMP integrated ecosystem observations of the islands of Maug provide a broad range of information: bathymetry and geomorphology, oceanography and water quality, and biological observations of corals, algae, fishes, and benthic macroinvertebrates along the forereef habitats of the islands of Maug. Methodologies and their limitations are discussed in detail in Chapter 2: "Methods," and specific limitations of the data or analyses presented in this Maug chapter are included in the appropriate discipline sections. Methods information and technique constraints should be considered when evaluating the usefulness and validity of the data and analyses in this chapter. The conditions of Maug's fish and benthic communities and the overall ecosystem relative to all the other islands in the Mariana Archipelago are discussed in Chapter 3: "Archipelagic Comparisons".

This section presents an overview of the status of coral reef ecosystems around the islands of Maug as well as some of the key natural processes and anthropogenic activities influencing coral reefs around these islands (for place-names and their locations, see Figure 16.2a in Section 16.2: "Survey Effort"):

- Maug includes 3 separate islands formed by the rim of a submerged caldera. Each island is characterized by a central ridge that is very narrow with steep slopes that end in sea cliffs at the coast. Their combined area of 2.14 km^2 makes these islands the smallest in the CNMI.

- No volcanic eruptions have been recorded at Maug in nearly 500 years. Active subsurface hydrothermal discharge was recorded within the Maug caldera in 2003 and a hydrothermal vent has been observed during the 3 MARAMP cruises.

- Maug is a protected reserve under the CNMI Constitution and inhabitation or building of permanent structures has been prohibited since 1978. The reserve was established for the protection of habitat for birds, wildlife, and plants. The islands of Maug and its waters and submerged lands are also included in the Islands Unit of the Marianas Trench Marine National Monument, which was established by presidential proclamation in January 2009.

- The outer flanks of the Maug volcano are steep, descending to a depth of ~ 2100 m north and east of Maug and to a depth of ~1700 m in the channel northwest of Maug. This channel separates Maug from Supply Reef. The submerged caldera of the Maug volcano lies at depths of 200–240 m, from which a twin-peaked submarine dome rises to a depth of 20 m.

- East of Maug, a complex area with steep slopes and high rugosity is present on the flanks, possibly a result of slumping from the crater wall. Bathymetry data show similar but smaller features southeast and west of Maug.

- Habitat complexity was medium to high through most of the areas surveyed by towed divers, except when surveys passed over a few sandy or silty patches.

- Generally, towed-diver surveys characterized habitats as hard substrates and recorded low levels of sand cover, relative to other areas surveyed in the Mariana Archipelago. Sand observed in deeper waters, during analyses of TOAD video footage, was related to topographic features with sand accumulating between ridges.

- Rapid (return periods of 12–24 h) drops in temperature (1°C–3°C) were observed in spring 2006 by STR moored off the west coast of West Island at a depth of 10 m. This signal was likely caused by an internal tide, generated when tidal currents interact with steep subsurface topography and result in high-frequency fluctuations in temperature and concentrations of dissolved nutrients and suspended particles that increase significantly from shallow reef crests to deep slopes.

- STR data show that temperatures in the west region and in the east caldera region reached the coral bleaching threshold in September 2006 but signs of significant thermal stress were not observed in these regions.

- Overall mean live coral cover was 21%–27% in the shallow waters surveyed by towed divers during the 3 survey years. Very little live coral cover was found in analyses of TOAD video footage recorded in deeper waters. Live coral cover was observed in TOAD video footage from a deployment on the central dome at a depth of ~ 160 m.

- The overall mean coral cover at Maug, estimated from 9 REA surveys, was 10.6% in 2007.

- Overall mean prevalence of coral disease was 0.02% at Maug in 2007. Four major disease states were found, including subacute tissue loss, skeletal growth anomalies, bleaching, and fungal infection. Out of the 9 sites surveyed, 4 contained disease. MAU-05 in the north region contained all 4 disease states and nearly 65% of cases. More than 60% of coral disease cases were observed on colonies of the genus Porites.

- Predation attributable to crown-of-thorns seastars (*Acanthaster planci*) or corallivorous snails was also observed at Maug, with an overall prevalence of 0.1%, a high level relative to results from other islands in the Mariana Archipelago.

- Overall mean macroalgal cover, observed during towed-diver surveys, decreased by 19% from 2005 to 2007. The forereef off the southwestern shore of West Island hosted greater macroalgal populations than elsewhere around Maug. This reef experienced less change, especially between MARAMP 2003 and 2005, when surveys conducted in other areas reported substantial changes over the same time period.

- Across the 3 MARAMP survey years, crustose coralline red algae were less abundant inside the caldera than on the outer flanks of Maug.

- Of the 9 REA sites surveyed at Maug in 2007, 3 contained algal disease. Only coralline lethal orange disease was recorded.

- Biomass of large fishes (≥ 50 cm in TL), estimated from towed-diver surveys, was moderate over the 3 survey periods, close to the average found at other unpopulated islands surveyed in the Mariana Archipelago. Observed biomass declined from 1.61 kg 100 m^{-2} in 2003 to 0.72 kg 100 m^{-2} in 2007.

- Biomass of fishes of all sizes at Maug, assessed by REA surveys, was among the lowest levels found at the unpopulated islands surveyed in the Mariana Archipelago, but still more than twice the average recorded at the populated, southern islands. In 2003, the observed overall mean of total fish biomass at Maug was 7.8 kg 100 m^{-2}, with the highest mean of 28.78 kg 100 m^{-2} recorded in the east region at MAU-03. In 2005, the overall mean of total fish biomass was 7.16 kg 100 m^{-2}, and MAU-01 in the west region had the greatest biomass of 13.57 kg 100 m^{-2}. In 2007, mean total fish biomass was 6.6 kg 100 m^{-2}, and the highest biomass of 15.78 kg 100 m^{-2} was found in the east caldera region at MAU-02.

- Mean species richness of fishes at Maug for the 3 MARAMP survey years was highest at REA sites located on the forereefs of the outer flanks.

- Giant clams were most abundant along the southern shore of North Island in the north caldera region and the western shore of West Island in the west region. Daytime abundance levels of sea cucumbers and sea urchins were low around Maug during the 3 MARAMP survey years, relative to results from other islands surveyed in the Mariana Archipelago.

- Crown-of-thorns seastars (COTS) were observed predominantly in the west caldera region during the 3 MARAMP survey years. In 2003, high densities of crown-of-thorns seastars (COTS), compared to other areas surveyed in the Mariana Archipelago, were recorded in a localized area in the west caldera region, suggesting a possible outbreak. The overall observed mean density of COTS was higher in 2003 than in 2005 and 2007.